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RESEARCH MEMORANDUM

A STUDY OF VISUAL INTERCEPTION ATTACKS ON A NONMANEUVERING AIRPLANE TARGET

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A STUDY OF VISUAL INTERCEPTION ATTACKS ON A NONMANEUVERING AIRPLANE TARGET

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SUMMARY

A study and evaluation of interception attacks made by an experienced pilot flying a Grumman F9F-3 airplane on a nonmaneuvering target have been made. The interception runs were made under visual conditions at subsonic speeds and at an altitude of 30,000 feet. The attacks were of the lead-pursuit type and the interceptor pilot utilized a computing type of gun-sight. The method used provides a good means of studying interceptor control characteristics and their relationship to tactical situations.

The general control procedure employed by the interceptor pilot during the runs has been determined as a sequence of five control phases. These phases were: (1) positioning of interceptor, (2) initial turn into target, (3) transition into lead-pursuit tracking, (4) lead-pursuit tracking, and (5) breakaway. This sequence of maneuvers is apparently a logical one that could be adapted to efficient automatic interceptor control by a system capable of programing maneuvers.

Several other factors which may be important in automatic control of an interceptor were in evidence during the tests. In cases where lead-pursuit navigation is desired, it may be necessary to incorporate in the autopilot tie-in a means for anticipating the turning rate (bank angle) required for smooth transition into tracking. Avoidance of buffet regions is important to the success of interception runs. This avoidance of buffeting is more than a problem of limiting the acceleration in that the control system should be designed so as to limit the type of attacks to those for which continuous tracking is possible without the necessity for undesirably high normal accelerations. Another point which may have automatic-control implications is that the interceptor pilot in the tracking phase of the runs generally used coordinated maneuvers and limited sideslip to low values. Many of the foregoing limitations could be avoided in cases where lead-collision navigation is possible. This type of attack is feasible only with armament which can be fired in salvo.

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A tactical evaluation of the interception runs has indicated that the starting position of the attack part of the run is a very important factor in determining the effectiveness of an attack. The simplest type of interceptor attack appeared to be that initiated from an overtaking encounter in which the flight paths of the two airplanes were parallel but laterally separated. Successful attacks were made from frontal and perpendicular encounters but only on runs in which the starting position was sufficiently separated from the target's flight path to allow the interceptor pilot to complete his sequence of maneuvers without needing to exceed the turning and rolling limitations of the interceptor.

The perpendicular encounters were in general the most demanding with regard to control rates, rates of roll, rates of change of interceptor line of sight to the target, and speed losses. In general, the maximum aileron control rates occurred in the initial turn phase of the attack, the maximum elevator control rates occurred in the transition into the tracking phase, and the maximum rudder control rates occurred in the tracking phase.

Tracking-error characteristics are discussed and values of computed standard deviation of tracking error are presented for various combinations of atmospheric turbulence and interceptor maneuvering acceleration. These standard deviations indicate a magnitude of the yaw and pitch components of about 2 mils in smooth air and slight acceleration. Either moderate turbulence or moderate maneuvering normal acceleration increased the standard-deviation values by a factor of about 3, and maneuvering normal accelerations near the maximum attainable increased them by a factor of 4.

INTRODUCTION

The development of techniques for all-weather radar-guided bombing together with tremendously effective bombs has made apparent the need for a commensurate defense. One form of defense is the aircraft interceptor, and much research is being directed toward the development of such a weapon. In order to be effective, the interceptor must be capable of all-weather operation, of intercepting an aircraft target in a minimum of time, and of efficient use of airborne ordnance with high kill probability. For such highly demanding performance specifications, it appears desirable to make the controlling element in the interceptor completely automatic.

Apparatus necessary for accomplishing automatically controlled interception is being developed, and the point has been reached where it is necessary to know what characteristics should be incorportated to provide successful operation. One approach to the problem of obtaining this information is based upon the belief that a study and evaluation of interception runs made by experienced pilots under visual conditions at subsonic speeds may provide a basis for determination of the characteristics of efficient interception control. Although the controlling operations of a human pilot executing an interception run under visual flight conditions are not wholly comparable to an automatically controlled interception, it is believed that the characteristics that make one system efficient may have similarity with those that make the other system efficient. For this reason, it was decided to conduct interception runs in which a series of relative orientations of an interceptor and a target airplane would be covered. The interceptor was provided with suitable instrumentation so that the controlling operations used could be studied, and ground radar was also provided to track the two airplanes so that the effect of the tactical situation could be assessed.

Since the data obtained in these tests were considered to be of value in their basic form, the presentation is in the form of time histories of the instrument recordings in the interceptor airplane together with time-correlated plots of the ground paths of the two airplanes.

APPARATUS

Interceptor airplane.- The airplane used as the interceptor during the flight test program was a Grumman F9F-3, Bureau No. 122560, a Navy jet fighter. A description of the airplane together with performance charts is presented in reference 1. Figure 1 shows a side-view photograph of the airplane. This airplane was equipped with a Mark 6 Mod 0 fire control system, but was otherwise void of the normal ordnance. This control system uses an MK 8 gyroscopically controlled lead-computing gunsight for lead-pursuit attacks. A lead-pursuit attack is an attack in which the interceptor flies a path relative to the target such that a projectile fired at any point along that path will collide with the target. It should be noted that the ranging element of the fire control system was inoperative during the flight tests and the range was set at a constant value of 1,000 feet. This resulted in the sights computing less than the required lead angle at ranges greater than 1,000 feet, and more than the required lead angle at ranges less than 1,000 feet. However, this condition did not affect the present study since the possible discrepancies in computed lead angle would have a negligible effect upon the procedures used by the interceptor pilot or the paths flown by the interceptor.

Standard NACA recording instruments were installed in the F9F-3 to record the following quantities: control-surface positions, control forces, linear accelerations along the three body axes, airspeed, pressure altitude, angle of attack of fuselage reference line, and angle of sideslip. A timing circuit common to all instruments provided instrument correlation. Most of the instrument installation is shown in figure 2. Figure 3 shows the nose boom installation which provided measurement of angle of sideslip and angle of attack, in addition to housing an airspeed head. A standard 16-millimeter gun camera was installed in the right wing position and was operated with the trigger provided on the control stick. A frame counter trace was available on one of the recording instruments to provide a time correlation between instrument records and gun-camera records. In addition, a 16-millimeter Fairchild CG-4 type gunsight camera was installed over the sight head to photograph the gunsight image and a reflected image of the target airplane and thus provide a means of analyzing tracking-error data. The CG-4 gunsight camera was operated by the same switch as the recording instruments and hence operated all the time that the recording instruments operated. It was possible to correlate this camera record with the instrument records by equally spacing the individual film frames over the length of the records taken.

Target airplane.- The airplane used as the target during the flight program was a North American F-51D, an Air Force fighter. No special instrumentation was employed in the F-51D.

Radar tracking equipment.- A modified SCR 584 radar tracking unit guided by an M-2 optical tracking system was used to record the ground paths of the two aircraft and to provide information on the wind conditions at the operating altitude by tracking the ascent of a free balloon. This equipment could plot the position of only one aircraft at a time, so a procedure was used in which the radar tracked the target airplane before and after the attack phase of the interception run and tracked the interceptor during that phase. This procedure required an interpolation of the target airplane position during the attack phase of the run, but this interpolation was feasible since in these tests the target flew straight-line courses at constant airspeed. Provisions were made to obtain a time synchronization between the radar data and the instrument recordings in the F9F-3.

TEST CONDITIONS

Operational.- It has been assumed for the present tests that an interception is basically a two-part affair. Part I is that required to get the interceptor to the location of the target at a given initial orientation and heading and is normally accomplished by ground control. Part II is that part of the interception run covered by the interceptor's attack upon the target. In the present flight program, part I of the interception run was prearranged by having the two airplanes depart from specified geographic points at a coordinated time and on such headings as were necessary to effect an interception in the general vicinity of the radar tracking installation. Part II of the interception run began at the discretion of the interceptor pilot any time after he sighted the target aircraft. This part covered the remainder of the interception run.

Three basic classes of interception runs were made. These are distinguished by the relative headings of the two airplanes at the time the target airplane was sighted by the interceptor pilot. The three classes are: (1) overtaking encounter, in which the interceptor is overtaking the target on a parallel course; (2) perpendicular encounter, in which the flight paths of the two airplanes are initially at about a right angle; and (3) frontal encounter, in which the flight paths are parallel but in opposite directions.

Interception runs were made on four flights in which instrument records together with radar tracking information were obtained. All runs were conducted at about 30,000 feet pressure altitude with only minor altitude differences between airplanes. The target airplane pilot was instructed to maintain a constant speed and heading throughout the interception run. The interceptor airplane was assigned various geographic starting points (depending upon the class of run to be made), an approximate course for interception of the target, and a speed corresponding to a Mach number of 0.75. The interceptor pilot was instructed to begin lead-pursuit types of attacks at his discretion after sighting the target. It was requested that the target tracking be pursued to minimum safe ranges and to avoid use of the airplane's airspeed brakes in order to keep the number of variables to a minimum.

Atmospheric.- Flights were conducted only on days having essentially cloud-free skies and excellent visibility. This was necessary since both airplanes were to be optically tracked at considerable ranges. The only atmospheric variables between flights that were considered of significance were the wind conditions prevailing at operating altitudes and the turbulence. No measurement was made of the air turbulence except that of a qualitative nature by the pilots. A brief summary of atmospheric conditions is presented in table I.

PRESENTATION OF DATA

For the data analysis a composite time history of the following quantities was made: (1) airspeed, (2) pressure altitude, (3) Mach number, (4) three components of linear acceleration, (5) control-surface position, (6) rolling velocity, (7) yawing velocity, (8) pitching velocity, (9) angle of sideslip, (10) angle of attack of fuselage reference line, and (11) pilot tracking error (where records were available). Except for quantities (1), (2), (3), and (11), these variations represent tracings of the film recordings of the interceptor's instruments. Items (1), (2), and (3) represent data reduced from the instrument recordings, and item (11) represents data analyzed from the CG-4 gunsight camera.

The tracking-error variation, item (11), consists of the pitch and yaw components of tracking error in mils. To determine the instantaneous values of this quantity, the CG-4 gunsight camera film was projected, frame by frame, on a set of Cartesian coordinates such that one coordinate was parallel with the span axis of the attacking aircraft and the origin was coincident with the pipper of the gunsight image. By measuring the coordinates of the assumed aiming point on the target aircraft with a scale calibrated in mils for the distance of projection used, the two components of tracking error were determined. These time histories are presented as the (a) parts of figures 4 to 28 grouped according to the classifications discussed in the section entitled "Test Conditions," that is, overtaking, perpendicular, or frontal encounters. As an additional indication of the time interval during which the interceptor pilot was tracking the target, the period of operation of the wing gun camera is noted on the time histories as "wing gun camera on." The pilot was instructed to use the gun camera only when tracking.

In order to give a more complete picture of the interception run, all the time-history figures include time-correlated ground-path plots of the two airplanes during the interception run. It should be noted that the position of the interceptor corresponds to the tip of the arrows, and the portion of the run in which the interceptor is tracking is denoted by the solid triangles.

A summary of figures 4 to 28 is presented in table II. It should be noted that only the tracking-error time history is presented in figures 16 and 17 due to difficulties in reproducing records of the other quantities.

As further presentation of each of the interception runs presented in the time-history figures, the ground-path plots have been analyzed to obtain relative position plots of the two airplanes with their headings corrected for wind conditions. These plots are presented as the (b) and (c) parts of figures 4 to 28. Part (b) of each figure shows the variation, coordinated with time, of the position of the interceptor airplane relative to the X- and Y-axes of the target airplane. The purpose of these plots is twofold: (1) to show the flight path relative to the target aircraft which an interceptor flies during typical attacks, and (2) to provide, for the benefit of organizations interested in bomber-defending fire-control systems, a means of determining what range and angular velocity inputs can be expected in a bomber's fire control system for the conditions of the present tests. Part (c) of each figure is a reverse plot showing the position of the target airplane relative to the interceptor. The purpose of these plots is to present the run as seen by the interceptor pilot. Such a plot indicates the variation of the angle between the interceptor's line of sight to the target and the interceptor's flight path. The plots also give an indication of the times during the run that the interceptor was tracking the target. The airplane, considered to be at the origin in each case, is heading in the positive X-direction. Corrections in headings due to sideslip angle, bank angle, and angle of attack have not been included.

CHARACTERISTICS OF INTERCEPTION RUNS

Overtaking encounters.- The overtaking encounters, presented in figures 4 to 8, are characterized by the interceptor flying on a course in the same direction and about parallel to that of the target airplane until the range closed to 3,000 or 4,000 yards. The interceptor then turned into the target and as the target came onto the sighting line of the interceptor the turn was reversed in order to permit tracking. It is of importance to note that for this type of run the interceptor pilot had the target airplane in sight for a considerable time before initiating the attack and chose the time to attack such that a different starting point with respect to relative orientation and/or range to target was obtained for each interception run.

Frontal encounter.- The frontal encounters, presented in figures 9 to 17, were characterized by the interceptor and the target approaching each other on approximately opposite courses and the interceptor either attempting a direct head-on attack or an attack in which the interceptor turned more or less 180° onto the tail region of the target airplane. In either case the interceptor pilot felt the necessity of a quick decision as to the type of attack to be carried out and initiated his attack immediately after sighting the target.

Perpendicular encounters.- The perpendicular encounters, presented in figures 18 to 28, were characterized by the interceptor approaching the projected flight path of the target at about a right angle and as the target passed in front of the interceptor a turn was made to track the target. In some cases it was necessary for the interceptor to maneuver slightly at the initiation of the attack to make sure the target would pass in front of the interceptor. There were also some cases (see figs. 26, 27, and 28) in which the interceptor passed in front of the target and then performed a repositioning maneuver that in effect led to another encounter.

RESULTS AND DISCUSSION

Interceptor Control Characteristics

General control procedures.- The interceptor runs conducted during the test program showed similarity in the general control procedure employed by the interceptor pilot, although the procedure was at times modified by circumstances peculiar to individual runs. The entire procedure starting from the position at which the interceptor pilot initiates the attack consists of five phases, more or less: (1) positioning of interceptor for attack; (2) initial turn into the target; (3) transition into lead-pursuit tracking; (4) lead-pursuit tracking of target; and (5) breakaway. The purpose of each step used will be discussed in more detail in the following sections which are devoted to a description of the control procedure used in each category of run, with the interesting features and deviations from general procedure for the individual runs included.

Overtaking encounter.- The essential features of the overtaking encounters are shown in figures 4 and 5. The purpose of the initial turn phase is to cause the target to traverse a path passing in front of the interceptor and to rapidly reduce the angle between the interceptor pilot's line of sight to the target and the interceptor pilot's tracking line. However, this turn is stopped short of reducing this angle to zero in anticipation of the requirement that the airplane must be banked in the opposite direction to that existing during the initial turn in order to develop the turning rate necessary to track the target. The interceptor pilot determines the position at which to begin the roll-out by judgment and experience so that time is afforded to perform this rolling maneuver, or so that the range at which the target will pass in front of the interceptor is consistent with the range at which he desires to initiate tracking of the target. It was the interceptor pilot's opinion that during this rolling maneuver the normal acceleration is not necessarily coordinated with the bank angle, but the pilot often rolls the airplane to the approximate attitude necessary to generate the required turning rate while maintaining a normal acceleration of roughly 1 g. As the tracking error angle approaches zero, a smooth merger of the line of sight and the tracking line is accomplished by the interceptor pilot's pulling normal acceleration to match the turning velocity of the interceptor with that required for tracking. This characteristic of the human pilot of anticipating the bank angle necessary to generate the required turning rate may merit consideration in choosing inputs to be tied into the autopilot of an automatic interceptor in that similar anticipatory characteristics may be needed.

In figures 4 and 5 both runs were initiated from a position behind the target's beam that allowed the interceptor pilot ample time to perform each phase of the control procedure. It is of interest to note that wing-gun camera records from the run shown in figure 4 indicated that the interceptor was banked about 35° to the left at the start of tracking, indicating the anticipation used by the pilot. In both runs the angle of sideslip was controlled within fairly narrow limits by the use of the rudder. The only notable difference between these two runs is that tracking was started at considerably longer range in the run shown in figure 4.

Figure 6 presents the time history of a run which was initiated from a position slightly ahead of the target's beam. Apparently there was insufficient lateral displacement of the flight paths for a successful run despite the efforts of the interceptor pilot to expedite his control procedures. In an effort to permit tracking, at normal firing ranges, the interceptor pilot continued the initial turn until the tracking line closely approached the line of sight to the target. This resulted in a rapid rate of closure of the angle between these two lines and the pilot attempted to perform the transition into the tracking phase by a fast reversal of the direction of turn. However, the range had closed so that the turning velocity required to track the target was greater than the interceptor could generate without entering the buffet region (a rate corresponding to 3g normal acceleration at the altitude of the tests). A possibility for making this run successful would have been for the interceptor pilot to make the initial turn even tighter than was used. The discreet employment of airspeed brakes during the initial turn phase of the attack might also have been helpful.

The runs shown in figures 7 and 8 are similar to those shown in figures 4 and 5 except for minor differences in starting position.

Frontal encounters.- As previously mentioned for the case of frontal encounters, the interceptor pilot at the instant of first sighting the target chose either to make a direct head-on attack or a 180° turn into a tail chase. If the choice was a direct head-on attack, the first procedure of the interceptor pilot is to maneuver so as to line up the flight path of the interceptor with that of the target. If this positioning phase is successful, it places the interceptor in a position to begin tracking the target.

Figure 9 shows a typical frontal encounter in which the interceptor pilot attempted to make a head-on attack. In observing the ground-path plot in figure 9, it must be remembered that this plot shows the resultant flight path of the two airplanes over the ground. Because of the wind direction and velocity, the actual headings of the two airplanes are about 7° off their ground paths into the wind. For a better indication of their relative headings and paths through the air mass, reference should be made to figure 9(b). At the initial long range (about 10,000 yards) the interceptor pilot obviously had trouble judging the path of the target because his first maneuver was to turn to the right toward the target, although such a maneuver would not help in alining the flight paths (see fig. 9(b)). The interceptor pilot quickly realized his mistake, so a turn was then made back to the left to get more closely alined. However, the time to complete this turn was limited by the high closing speeds, and as a result the pilot was unable to line up the interceptor on the target's path. In an effort to accomplish some tracking, the interceptor pilot turned into the target and attempted a transition into tracking at about 20 seconds. The interceptor was unable to generate the required turning velocity and consequently the interceptor pilot could only rake the tracking line through the target as he pulled the interceptor into the buffet region. Perhaps a more successful run might have been accomplished if the pilot had made the transition into lead-pursuit tracking immediately on sighting the target. This procedure was not investigated, however.

Figure 10 shows a head-on attack from a frontal encounter in which the interceptor pilot did a creditable job of alining the flight path of the interceptor with that of the target. However, the two airplanes had closed to what the interceptor pilot considered minimum range before the tracking line could be brought to bear on the target, and a breakaway was executed without tracking the target.

These two head-on attacks show typical examples of the difficulties that confront an interceptor pilot attempting head-on attacks. Such attacks would be more feasible for a rocket-bearing interceptor flying lead-collision courses.

The second possible choice of a 180° turn onto the tail region of the target allows a more straightforward use of the general control procedure. In such attacks there is normally little time to adjust the position of the interceptor except by delaying the initial turn. The interceptor pilot apparently could judge quite adequately the position at which to initiate this turn. The initial turn was varied, as was dictated by the range and lateral displacement at the point of first visual contact, so as to accomplish a smooth entry into a curve of pursuit. The latter portion of the initial turn may be modified to serve the purpose of controlling the range at which the transition into tracking is initiated.

Figures 11, 12, 13, and 14 present well-executed attacks from frontal encounters in which sufficient lateral displacement existed for the type of attack consisting of a 180° turn onto the target tail region. The only notable difference in the four encounters was the lateral displacement at the initiation of the attack with the encounter shown in figure 11 being at the greatest displacement and that shown in figure 14 being at the least displacement.

It is of interest to note that two methods of accomplishing the transition into the tracking phase were employed by the interceptor pilot on this type of attack. On the runs where large lateral displacement of the initial flight paths of the two airplanes existed, he usually continued the initial turn until the interceptor tracking line was ahead of the target. The rate of turn was then reduced to allow the line of sight to approach the tracking line for the transition into tracking. Such a procedure may be used where it is desired to close rapidly to shorter ranges before tracking is begun. In addition, the transition into tracking for the cases where the tracking line is ahead of the target appears to be more easily accomplished by the pilot. Where the lateral displacement of the flight paths was not large the interceptor pilot usually accomplished the transition into the tracking phase by pulling the tracking line up to the line of sight.

Figure 15 presents an encounter in which insufficient lateral displacement existed to execute a successful attack. At the start of the run, the interceptor pilot apparently tried to improve his position by a turn to the right to open the lateral range. However, there was insufficient time for this turn to develop before the interceptor pilot had to reverse the direction of bank angle and attempt to turn onto the target; the attempt was unsuccessful.

Perpendicular encounters.- The control procedure involved in an attack from a perpendicular encounter differed from the others previously described principally in the positioning and initial turn phases. As the interceptor approached the flight path of the target and initiated an attack there were three courses of action that the interceptor pilot was likely to take: (1) if the initial orientation appeared satisfactory he merely waited until the target approached the tracking line and turned as required for the transition into tracking; or (2) if the initial orientation did not appear to allow the target to pass in front of the interceptor at an acceptable range a turn was made toward the target that allowed an earlier transition into the tracking phase; or (3) if the initial orientation was unfavorable for a perpendicular attack a maneuver was performed to place the interceptor into position for another encounter. The choice of the course of action by the interceptor pilot was dependent upon the range at which the target was first sighted as well as the relative time the two airplanes would cross the intersection of their projected flight paths if the interceptor did not maneuver. The range at which the target was first sighted affected the choice of the course of action in that if the initial range was great enough the interceptor pilot could adjust the relative time that the two airplanes would cross the intersection of their projected flight paths if the interceptor did not maneuver.

An example of a simple turn into tracking from a perpendicular encounter is shown in figure 18. However, in this case the pilot had little choice as to the course of action due to a late sighting of the target. The transition into the tracking phase was effected at too great a deflection angle at close range and was unsuccessful because the turning-velocity requirements for tracking were too great. As a result, the interceptor overshot the target flight path and the pilot was unable to track until a tail-chase position was reached.

Examples of perpendicular encounters from which an initial turn toward the target was taken are shown in figures 19, 20, 21, 22, 23, 24, and 25. The initial turn toward the target is somewhat similar to that used in an overtaking encounter when the starting position is ahead of the target's beam but transition into the tracking phase is more abrupt and more difficult to accomplish than for the overtaking encounters starting behind the beam position. In the majority of these cases the interceptor pilot's tracking was interrupted because in an attempt to continue tracking the pilot pulled the interceptor up into a stalled condition where severe buffeting existed and where further normal acceleration could not be developed. In this situation the required turning velocity for tracking became greater than that which could be generated by the interceptor. Reference to figure 19 shows the interruption of tracking as the normal acceleration reached a maximum value and then a continuation of tracking when the interceptor reached a tail-chase position and the required turning velocities for tracking were again low. The run presented in figure 21 could probably have been better handled by maneuvering for a reencounter. The run presented in figure 22 was executed without an interruption of tracking, although it was necessary that the interceptor be held at such high normal acceleration that buffeting was present during the tracking.

Figures 26, 27, and 28 present runs in which the interceptor was early at the intersection and the pilot chose to continue his course until a repositioning turn would put the interceptor into position to reencounter the target. It is of interest to note that in the run shown in figure 26, the interceptor pilot did not sight the target airplane after the repositioning turn.

Tracking Characteristics

The tracking-error variation shown in the time histories was analyzed to determine the standard deviations of the tracking-error components. The interval during the run over which these standard deviations were computed was chosen to exclude the transition into the tracking phase and any breakaway from tracking, whether intentional or inadvertent. These standard deviations and time intervals are presented in table III.

Tracking-error magnitude.- Since the target did not perform any significant maneuvers, the magnitude of the tracking-error variation would appear to be primarily dependent upon five factors: (1) pilot learning cycle, (2) atmospheric turbulence, (3) maneuvering normal acceleration of the interceptor, (4) dynamic characteristics of the interceptor, and (5) dynamic characteristics of the gunsight. The last two factors were not studied except by noting that the lateral oscillations of the interceptor were poorly damped and that from an observation of the CG-4 gunsight camera records and the wing gun camera records the sight had a definite smoothing effect upon the apparent movement of the gunsight image with respect to the target.

The effect of pilot learning cycle on the tracking-error magnitude was believed to be negligible in the test flights because the interceptor pilot was experienced in making lead-pursuit tracking runs.

The tracking-error magnitude attributable to the factors of atmospheric turbulence and interceptor maneuvering normal acceleration was not assessed because these factors were not varied independently. However, by grouping the runs, or parts of the runs, according to the degree of turbulence or magnitude of acceleration, a qualitative analysis is possible. The average standard deviation of tracking error in mils of these groups is as follows:

Normal acceleration, g units	No turbulence		Slight turbulence		Moderate turbulence	
	Yaw, mils	Pitch, mils	Yaw, mils	Pitch, mils	Yaw, mils	Pitch, mils
0 to $1\frac{1}{4}$	2.1	1.8	3.8	1.8	6.5	3.2
$1\frac{1}{4}$ to 2			6.3	5.8	6.7	5.8
2 to $2\frac{3}{4}$			9.8	4.9	7.1	4.5
$2\frac{3}{4}$ +					9.9	7.8

These average standard deviations of tracking error should be viewed with some caution since the data available were not extensive and the groupings were of necessity somewhat arbitrary. Also other factors (such as range and rate of change of acceleration) which may have an appreciable effect upon tracking error were varied during the runs analyzed. The indications are, however, that turbulence is a primary cause of tracking error only when the normal acceleration is low and, for the test airplane, affects the yawing component much more than the pitching component. Also there was a roughly linear increase in tracking error with increasing normal acceleration. Qualitatively, it appears that moderate turbulence or moderate normal acceleration $\left(1\frac{1}{4}g \text{ to } 2g\right)$ increased the magnitude of tracking-error components from that in smooth air by a factor of about 3, and that moderate turbulence combined with high acceleration $\left(\text{over } 2\frac{3}{4}g\right)$ increased the tracking-error components by a factor of about 4.

Frequency content of tracking errors.- In a study of tracking errors the frequency content of these errors is of value in pointing out the source of these errors. Therefore, the frequency content of some of the tracking-error variations shown in figures 4 to 28 were determined through use of a harmonic analyzer of the Dent-Draper Model, Rolling Sphere Type (ref. 2). A typical result is presented in figure 29 which presents an analysis of the part of the tracking-error variation in figure 22 between 17.5 and 31.5 seconds. The general result obtained from all of the analyzed variations is that high harmonic content existed at two distinct ranges of frequency, one of which is about the frequency of the interceptor lateral oscillation. The lateral oscillation apparently affects both the yaw and pitch components of the tracking error due to the cross-coupling that is present in the motions of the airplane due primarily to gyroscopic effects of the engine. During portions of the runs where low values of normal acceleration were recorded the effect of the lateral oscillation was much greater on the yaw component than on the pitch component; however, whenever moderate normal accelerations were recorded the pitch component was also strongly affected. The other frequency is of a lower order and varies somewhat for different runs, being on the average about 1/8 cycle per second. In addition to these two frequencies, a third frequency is present in the pitch component of the tracking error when the airplane is experiencing heavy buffeting, and is about $1\frac{1}{4}$ cycles per second.

Tracking control procedures.- One of the principal objectives of the present study was to determine the control procedures used by the pilot in his attempt to keep the tracking error to a minimum. Only two runs (presented in figs. 4 and 5) were made in which conditions were such as to permit a rough analysis of this factor. In both these figures the tracking-error variation shows appreciable magnitude, and it is possible to pick out the control response to this variation since the control requirements from other sources is thought to be negligible. As may be seen in these figures, the aileron and rudder controls are applied in a logical direction to reduce the azimuth component of the error and, since the sideslip angle remains at a low value, the indication is that the controls were applied in a coordinated manner. Because of the small amount of data, no attempt has been made to analyze such factors as the phase angle and amplitude relationship between the control movements and the tracking error.

The data obtained from the present tests indicate that the control procedures used by the interceptor pilot during the tracking phase of his attack will be a difficult factor to detect because of the inherent complexities involved when tracking on a lead-pursuit type of attack. There are three primary sources of the tracking error which stimulates the interceptor pilot to manipulate his controls during an attack: (1) the general control of the attack requires continuous control manipulation since a lead-pursuit attack usually calls for a continuous change of normal acceleration which would be coupled with trim or speed changes; (2) the tracking errors that arise require corrective control applications; and (3) extraneous disturbance such as rough-air gusts require corrective control applications. These three factors are closely interrelated so that the control manipulation in response to one source of error tends to mask those required by the other sources.

Effect of Interceptor Turning Capabilities

As was evidenced in several of the runs discussed in the section "Interceptor Control Characteristics," there is a region relative to a target airplane within which an interceptor airplane would be unable to generate the turning velocity required to track the target. Reference 3 presents equations from which the boundary of this region can be calculated. The range of this boundary relative to the target is shown to be a function of (1) target speed, (2) attacking airplane speed, (3) projectile speed, (4) maximum attainable normal acceleration of the attacking airplane, and (5) attacking angle relative to the target. The complete equation includes terms that are a result of the variation of the lead angle with the attacking angle. In the present test conditions the contribution of the lead-angle terms is small and for practical purposes may be neglected. The resulting boundary on either side of the target is described by a circle.

Under the conditions of the present flight tests the interceptor began buffeting at about 3.0g and acceleration peaks were recorded as high as 3.9g. An inspection of runs such as shown in figure 22 indicated that the maximum average normal acceleration utilized by the interceptor was about 3.4g. Using this value of normal acceleration in the formula from reference 3 gives a circular region relative to the target airplane having a diameter of 1400 yards.

These circles which represent the invulnerable attack region are plotted on the (b) parts of figures 4 to 28. A close examination will show that these circles are substantiated in every figure since at no time is the interceptor tracking when it is in the calculated invulnerable region relative to the target. On several runs there is close agreement between the time at which tracking of the target was interrupted (as shown in the (a) parts of figs. 19, 23, and 24) and the time at which the interceptor entered the invulnerable attack region (as shown in the (b) parts of figs. 19, 23, and 24).

Data Significant to Design of Interceptor Control Systems

The time histories of the interception runs include several factors that are of possible significance to designers of interceptor control systems. In order to tabulate the data pertinent to these factors, the interception runs were divided into the various phases of attack, as previously discussed. For the most part a logical division of these attack phases was apparent although some overlapping was often present. No attempt was made to discriminate between positioning and initial turn phases, and data falling within these phases were credited to the initial turn phase. For interception runs such as the perpendicular runs presented in figures 19, 23, and 24, the portion of the attack immediately following the initial interruption of tracking was arbitrarily classified as being part of the transition into tracking phase. The factors analyzed include the following:

Control rates: Table IV presents a summary of the maximum control rates analyzed for the left aileron, rudder, and elevator of the interceptor airplane for each class of attack.

Control deflections: Table V presents a summary of the maximum control-surface deflections for the ailerons, rudder, and elevator of the interceptor airplane from the level-flight trim position that existed at the start of the runs. These trim positions were about the same for all runs and were: total aileron deflection equals 0.0°, rudder deflection equals 0.9° left, and elevator deflection equals 0.6° down.

Control forces: Table VI presents a summary of the maximum control-stick and rudder-pedal forces analyzed for each attack phase.

Rate of roll: Table VII presents a summary of the maximum rolling angular velocities recorded for each attack phase.

Rate of change of interceptor line of sight: Table VIII presents a summary of the maximum rates of change of the interceptor's line of sight during successful interception runs. The table excludes those frontal encounters which resulted in head-on attacks (figs. 9 and 10) and other encounters in which the interceptor passed the target at close range without effecting any steady tracking (figs. 6 and 21).

Interceptor speed losses: Table IX presents a summary of the maximum speed losses occurring during each of the interception runs. These data apply to the over-all run rather than to a particular phase.

The data presented in tables IV to IX indicate several characteristics of the interceptor pilot's control operation and the resulting interception runs that are worthy of note.

General.- From practically all aspects, the perpendicular type of encounter was the most demanding with the exception of the frontal encounters resulting in head-on attacks. Higher control rates, deflections, and forces were applied and higher rolling rates were used for the perpendicular encounter; in addition, the rate of change of the interceptor line of sight to the target and airspeed losses were greater. These observations apply particularly during the phases before actual tracking of the target was established. The overtaking class of encounter was by far the least demanding from the standpoint of most of the characteristics tabulated.

Aileron control.- During all classes of encounters the interceptor pilot moved the ailerons at appreciably higher rates in the initial turn phase than in the other attack phases (see table IV). The highest maximum rates in the initial turn and transition into tracking phase occurred during perpendicular encounters; the maximum rates during overtaking encounters were relatively much lower in these phases. The maximum aileron deflections and rates of roll were only moderate compared to the capabilities of the airplane. These rates were only about half of the values available (see tables V and VII). Since the F9F-3 airplane has aileron boost, the control forces were very light (table VI) and were not the limiting factor on rolling performance. Evidently, the maximum roll rate of somewhat over 1 radian per second was considered by the pilot to be the highest which afforded precise control of roll attitude since in several instances higher rates would have been advantageous in performing transition into tracking.

Rudder control.- The maximum rudder deflections were always small and varied only slightly between the different attack phases and classes of encounters (table V). The pedal forces were quite heavy and therefore may have been a limiting factor in the use of the rudder. It is significant that the rate of rudder deflection was generally higher in the tracking phase indicating that the pilot was attempting to make more precise use of this control in that phase.

Elevator control.- As with the other controls the elevator control effectiveness was more than adequate. The elevator control forces were moderately heavy. The highest elevator rates and deflections occurred in the transition into tracking phase although relatively high rates also occurred in the initial turn phase of perpendicular encounters and relatively high deflections occurred in the tracking phase. Much lower elevator rates, deflections, and forces were used in the overtaking encounters than in the other types. The limiting factor in regard to the magnitude of elevator deflection and force was the onset of airplane buffeting.

Evaluations Applied to Automatic Control Apparatus

The evaluation of interception runs made for the present study indicates some characteristics that would be desirable to incorporate in the control apparatus of an automatic interceptor designed for lead-pursuit attacks. A flight limitation that should be taken into account is the roll rate and roll acceleration capabilities of the interceptor. This factor is of importance because it determines the time required to adjust the turning velocity with a resultant effect upon the flight distance covered during certain phases of the general control procedure and in particular the ability to perform a transition into the tracking phase. Probably the most significant characteristic observed in the controlling operation of the interceptor pilot during the flight tests was the anticipation of roll angle needed to generate the required turning velocity for tracking the target airplane. This anticipation enabled a smooth transition into the tracking phase.

The entire sequence of control operations employed by the interceptor pilot in the majority of interception encounters, however, is apparently a logical one that might be adapted to automatic control by a system of programed maneuvers. In order to use such a controlling procedure efficiently, the automatic control apparatus would have to be capable of discriminating between starting positions on the basis of their possibilities for a successful attack and, if advisable, be capable of repositioning the interceptor. This operation was adequately handled by the interceptor pilot on runs in which the initial sighting of the target was at long range, with the exception of encounters that resulted in head-on attacks.

In order to discern correctly the type of attack needed or possibility of success of an attack originating from a given starting position, the interceptor control apparatus should be cognizant of certain flight limitations of the interceptor. As was noted in the present study, the limitation of turning capability is of prime importance in determining regions relative to a target airplane within which an interceptor can track the target. It is advantageous from this standpoint to be able to utilize the maximum turning capability of the interceptor; however, doing this may result in severe airplane buffeting. Since buffeting has been shown to result in loss of tracking accuracy as well as undesirably large losses in airspeed, a need is indicated for having an automatic system limit attacks to those which will avoid such conditions.

The present results indicate that airspeed changes, in general, affect the success of an interceptor attack and therefore consideration should be given to the control of airspeed in an automatic system.

Another point which may have automatic-control implications is that the interceptor pilot in the tracking phase of the run generally used coordinated maneuvers and limited sideslip to low values.

CONCLUDING REMARKS

This study and evaluation of human-pilot-controlled interception runs utilizing lead-pursuit navigation against a nonmaneuvering airplane target has indicated the following concluding remarks:

1. The general control procedure employed by the interceptor pilot during the runs has been determined as a sequence of five control phases. These phases were: (1) positioning of interceptor, (2) initial turn into target, (3) transition into lead-pursuit tracking, (4) lead pursuit tracking, and (5) breakaway. This sequence of control is a logical one that might be adapted to efficient automatic interception control by a system capable of programing maneuvers.

2. The results indicate several factors which may be important in automatic control of an interceptor where lead-pursuit navigation is desired. These factors include anticipation of the turning rate (bank angle) required for tracking so that a smooth transition into the tracking phase can be made, and the use of coordinated maneuvers, wherein the sideslip angle is limited to low values.

3. A desirable feature of automatically controlled interceptors flying lead-pursuit courses would be an ability to discriminate between attack starting positions in order to limit attacks to those that will not require the interceptor to fly at high normal accelerations. In cases where an effective attack is not feasible the control apparatus should be capable of repositioning the interceptor.

4. The tactical effectiveness of the runs investigated may be summarized as follows:

(a) The overtaking encounters were usually successful except for the case where the starting position was forward of the target's beam.

(b) Frontal encounters were unsuccessful when they developed into a head-on attack, but were successful when sufficient separation existed to enable a 180° turn to be made onto the target's tail region.

(c) Some perpendicular encounters were successful but these encounters were quite critical as to the timing of the attack and the initial separation between the airplanes.

5. The perpendicular class of encounter was the most demanding from a standpoint of control rates, rates of roll, rates of change of interceptor line of sight to the target, and speed losses.

6. The maximum aileron control rates occurred in the initial turn attack phase; the maximum elevator control rates occurred in the transition into tracking phase; and the maximum rudder control rates occurred in the tracking phase.

7. Computed standard deviations of tracking errors, averaged to present representative values for various combinations of atmospheric turbulence and interceptor normal acceleration, indicate that in smooth air and slight acceleration the yaw and pitch components were about 2 mils. Either moderate turbulence or moderate normal acceleration increased the standard deviation values by a factor of about 3, and normal accelerations near the maximum attainable increased them by a factor of 4. In general, the yawing component was more affected by turbulence than the pitch component.

8. A harmonic analysis of some of the tracking-error variations indicates that the pitch and yaw components are composed of two predominant frequencies. One of these frequencies is about 1/2 cycle per second (corresponding to the interceptor lateral oscillation frequency) and the other is lower, averaging about 1/8 cycle per second. When in the buffeting region, the pitch component also contained a frequency around $1\frac{1}{4}$ cycles per second.

9. Consistent agreement existed between the relative positions at which the interceptor was unable to track the target and these positions as predicted from the equations presented in Ballistic Research Laboratory Memorandum Report No. 462.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 14, 1953.

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1. Anon: Pilot's Handbook for Navy Models F9F-2, -3 Aircraft. AN 01-85FGA-1, U. S. Air Force and Bur. Aero., July 1, 1951.

2. Magrath, Howard A.: AMC Harmonic Analyzers, Rolling Sphere Type; Instructions for Operation, Maintenance and Shipment. Memo. Rep. No. MCREXA5/HAM/rah, Air Materiel Command, Eng. Div., U. S. Air Force, Dec. 20, 1948.

3. Weiss, Herbert K., and Stein, Arthur: Airplane Vulnerability and Overall Armament Effectiveness. Memo. Rep. No. 462, Ballistic Research Lab., Aberdeen Proving Ground, May 21, 1947.

TABLE I.- SUMMARY OF ATMOSPHERIC CONDITIONS

Flight	Visibility	Sky coverage	Turbulence	Wind
1	Excellent	Clear	Slight	22 knots/297°
2	Excellent	Clear	None	55 knots/259°
3	Excellent	Clear	Moderate	62 knots/320°
4	Excellent	Clear	Slight	82.5 knots/262°

TABLE II.- SUMMARY OF ENCOUNTERS

Figure	Flight	CG-4 gunsight camera records	Wing-gun-camera records
Overtaking encounters			
4	4	Yes	Yes
5	1	Yes	No
6	1	Yes	No
7	1	Yes	No
8	4	Yes	Yes
Frontal encounters			
9	3	Yes	Yes
10	4	No	No
11	2	No	No
12	3	Yes	Yes
13	4	No	Yes
14	4	No	Yes
15	3	Yes	No
16	2	Yes	Yes
17	2	Yes	Yes
Perpendicular encounters			
18	2	No	No
19	3	Yes	Yes
20	4	No	No
21	3	Yes	Yes
22	3	Yes	Yes
23	3	Yes	Yes
24	4	Yes	Yes
25	2	No	No
26	2	No	No
27	2	No	No
28	3	Yes	Yes

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TABLE III.- STANDARD DEVIATIONS OF TRACKING ERROR

Figure	Time interval, sec	Standard deviation in yaw, mils	Standard deviation in pitch, mils
Overtaking encounter			
4	23.1 to 41.6	5.6	2.6
5	26.9 to 39.6	7.0	4.3
7	14.4 to 38.0	4.6	2.1
8	20.0 to 41.5	2.6	2.0
Frontal encounter			
12	22.2 to 51.6	6.7	2.2
16	113.0 to 137.0	2.6	2.4
17	60.4 to 89.2	1.7	0.9
Perpendicular encounter			
19	10.4 to 17.9	10.7	9.6
19	38.2 to 47.4	4.1	4.1
22	17.7 to 50.8	6.9	6.1
23	10.1 to 19.8	8.1	3.8
23	34.6 to 45.7	6.1	2.5
24	43.3 to 70.0	4.4	3.8

TABLE IV.- MAXIMUM CONTROL RATES

Phase	Control	Maximum control rates, deg/sec, for -		
		Overtaking encounter	Frontal encounter	Perpendicular encounter
Initial turn	Left aileron	25	45	56
	Rudder	11	8	11
	Elevator	8	6	22
Transition	Left aileron	22	15	45
	Rudder	11	12	39
	Elevator	7	23	32
Tracking	Left aileron	18	25	17
	Rudder	15	22	20
	Elevator	5	8	13
Breakaway	Left aileron	14	15	12
	Rudder	8	8	8
	Elevator	10	14	14

TABLE V.- MAXIMUM CONTROL DEFLECTIONS

Phase	Control	Maximum control deflections, deg, for -		
		Overtaking encounter	Frontal encounter	Perpendicular encounter
Initial turn	Total aileron	15.9	19.9	16.1
	Rudder	2.1	1.2	1.4
	Elevator	2.8	7.0	3.9
Transition	Total aileron	6.9	7.5	15.9
	Rudder	2.3	3.5	4.3
	Elevator	2.0	9.7	11.8
Tracking	Total aileron	3.8	14.5	10.8
	Rudder	1.7	3.1	2.9
	Elevator	1.8	9.0	8.8
Breakaway	Total aileron	11.2	11.5	9.1
	Rudder	1.0	7.4	1.9
	Elevator	1.2(down)	1.6(down)	3.1

TABLE VI.- MAXIMUM CONTROL-STICK AND RUDDER-PEDAL FORCES

Phase	Control	Maximum control forces, lb, for -		
		Overtaking encounter	Frontal encounter	Perpendicular encounter
Initial turn	Aileron Rudder pedals Elevator	8 right 47 right 31 pull	12 right 63 right 55 pull	12 right 47 left 27 pull
Transition	Aileron Rudder pedals Elevator	7 right 60 right 24 pull	7 left 132 left 49 pull	7 right 101 right 63 pull
Tracking	Aileron Rudder pedals Elevator	4 right 53 right 15 push	9 right 112 left 57 pull	8 right 78 left 35 pull
Breakaway	Aileron Rudder pedals Elevator	6 right 54 right 20 push	7 right 63 right 30 push	3 left 65 left 60 push

TABLE VII.- MAXIMUM RATES OF ROLL

Phase	Maximum rates of roll, radians/sec, for -		
	Overtaking encounter	Frontal encounter	Perpendicular encounter
Initial turn	1.35	1.23	1.38
Transition	.65	.67	1.38
Tracking	.37	1.02	.74
Breakaway	1.05	1.00	1.08

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TABLE VIII.- MAXIMUM RATE OF CHANGE OF INTERCEPTOR

LINE OF SIGHT TO TARGET

Phase	Maximum rate of change of interceptor line of sight to target, deg/sec, for -		
	Overtaking encounter	Frontal encounter	Perpendicular encounter
Initial turn	6	4	14
Transition	4	6	14
Tracking	3	0	9

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TABLE IX.- INTERCEPTOR SPEED LOSSES

Figure	Maximum speed loss, mph	Percent loss
Overtaking encounter		
4	15	2.9
5	19	3.8
6	40	7.7
7	9	1.8
8	22	4.2
Frontal encounter		
9	33	6.4
10	43	8.3
11	7	1.4
12	29	5.7
13	39	7.5
14	89	17.2
15	81	16.0
Perpendicular encounter		
18	41	7.9
19	97	18.9
20	117	21.9
21	18	3.5
22	65	12.3
23	143	27.3
24	109	21.5
25	22	4.8
26	123	25.1
27	66	12.8
28	76	15.3

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Figure 1.- Grumman F9F-3 airplane.

[redacted]

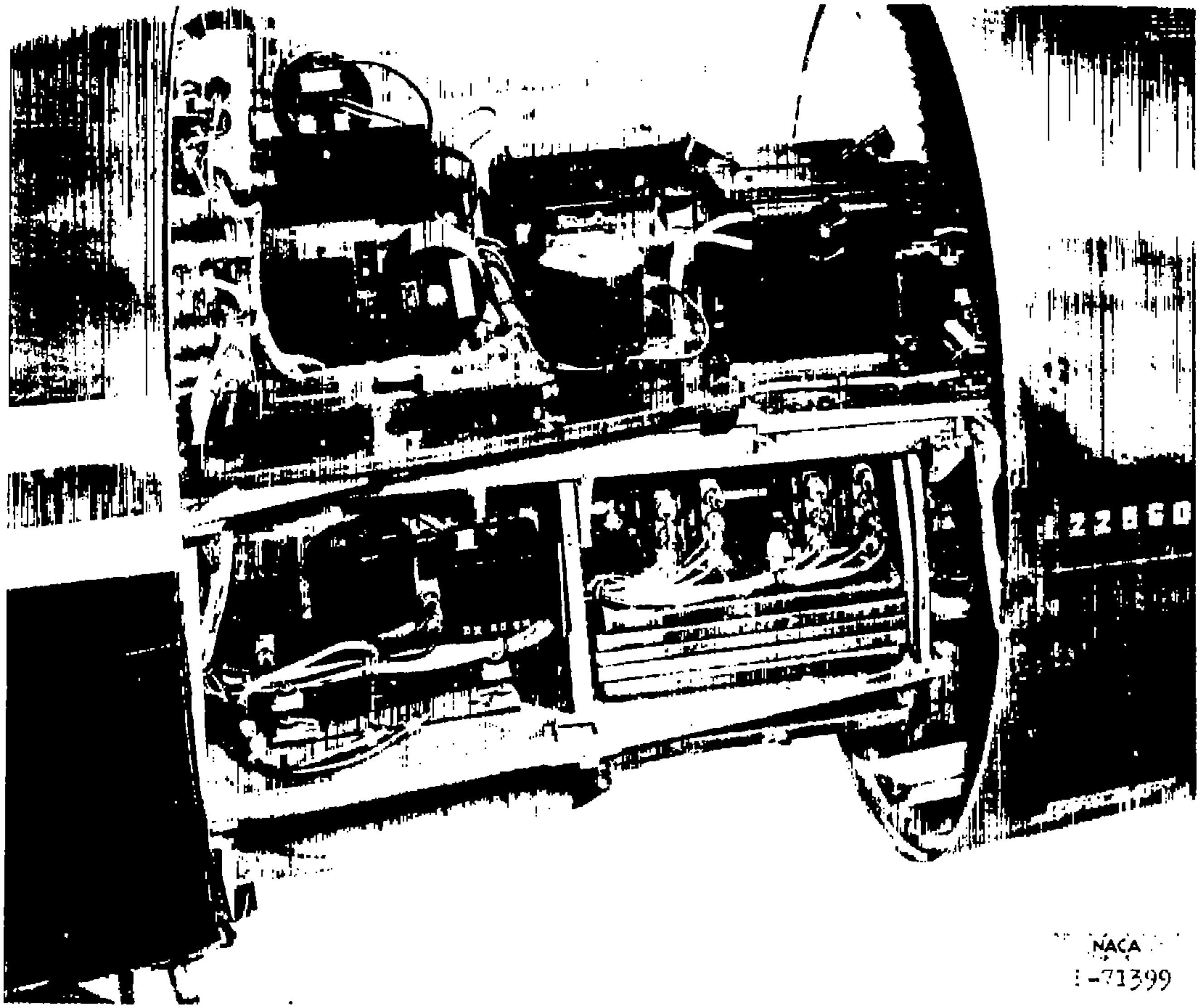
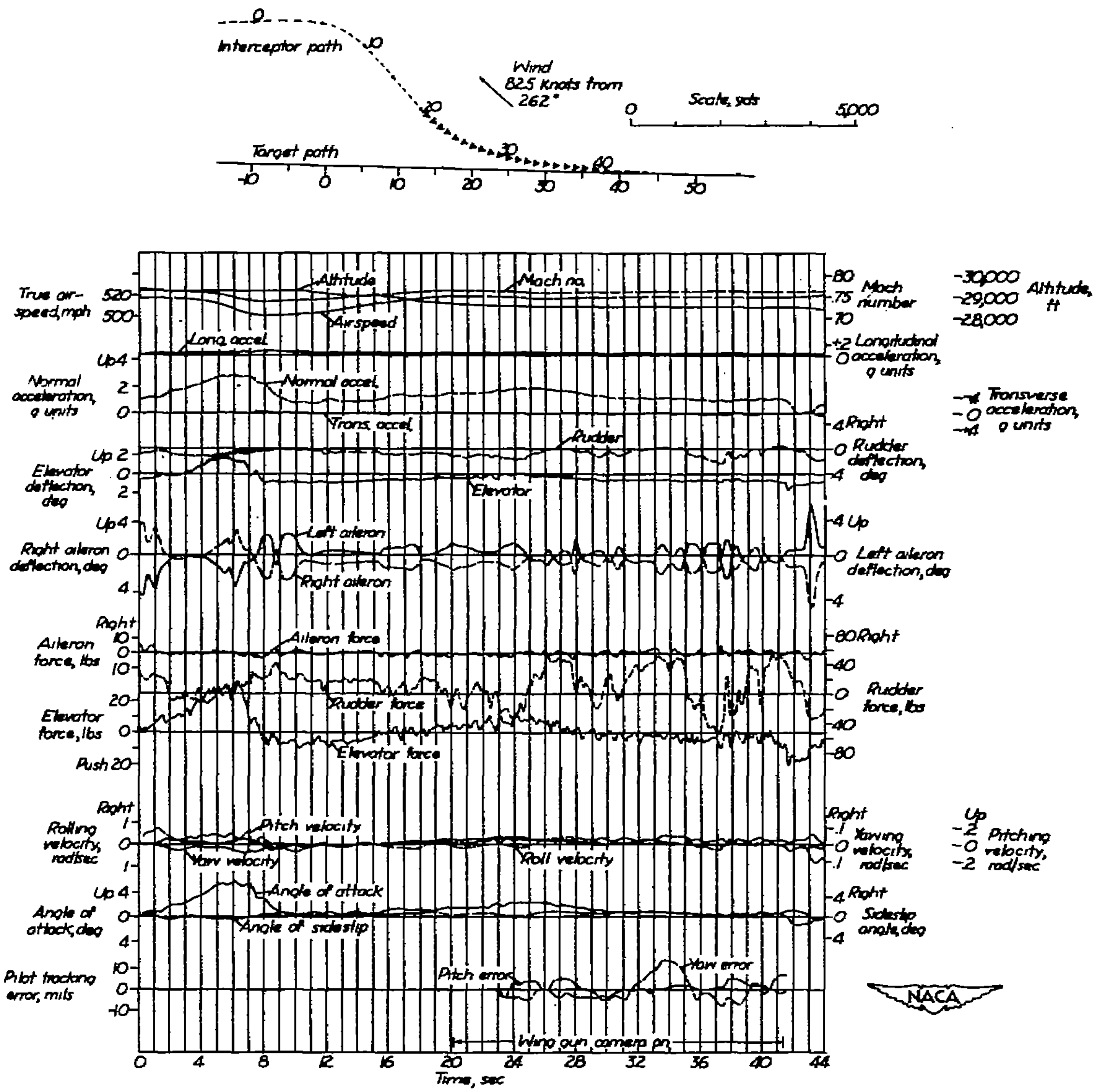


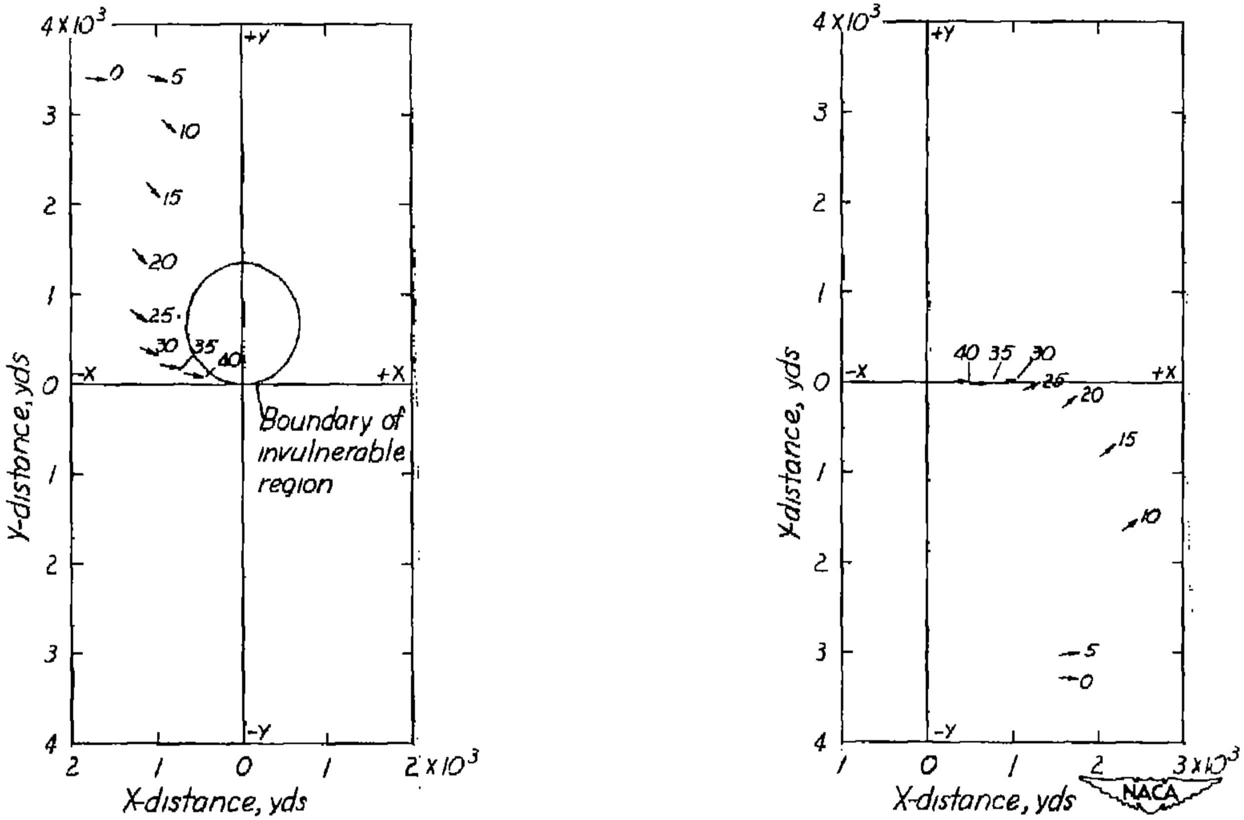
Figure 2.- Instrument installation in nose compartment of Grumman F9F-3 airplane.

Figure 3.- Nose-boom installation on Grumman F9F-3 airplane.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

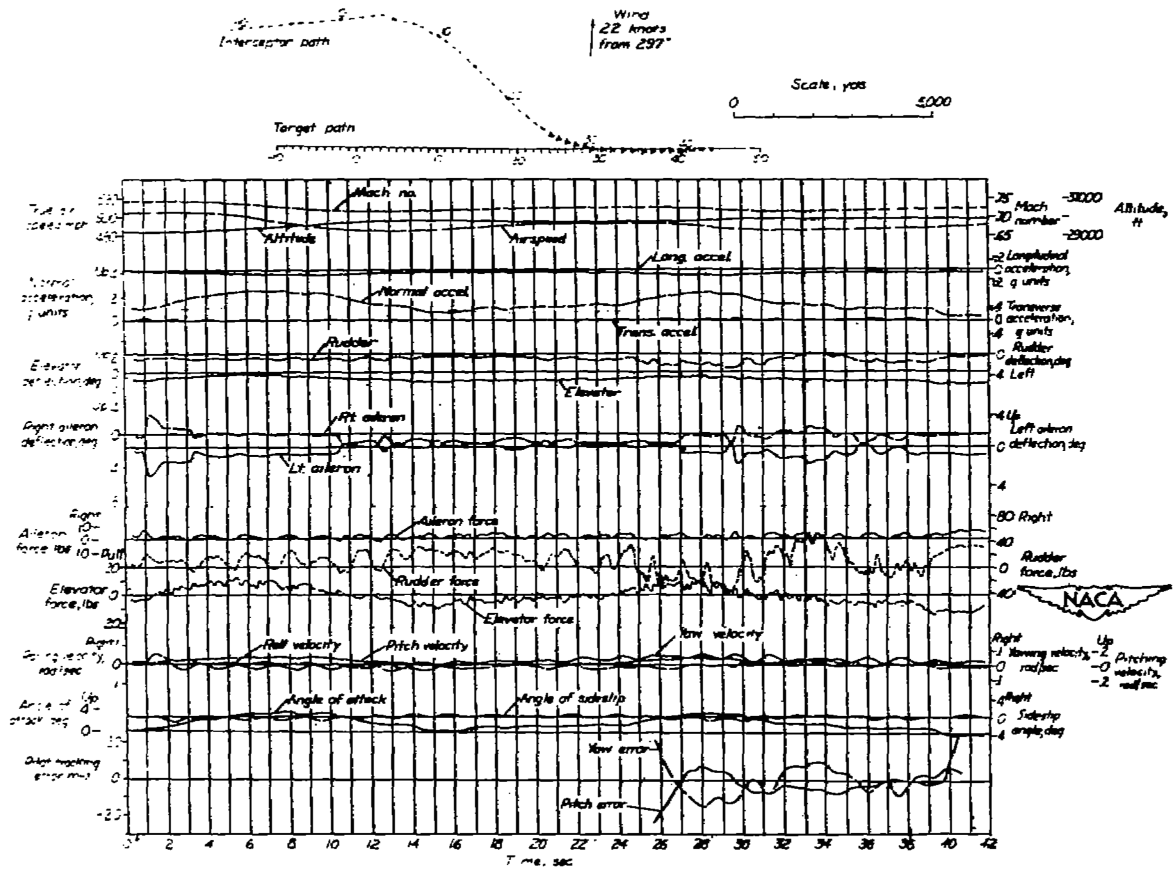
Figure 4.- Interceptor airplane attacking target airplane from an overtaking encounter.



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 4.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 5.- Interceptor airplane attacking target airplane from an overtaking encounter.

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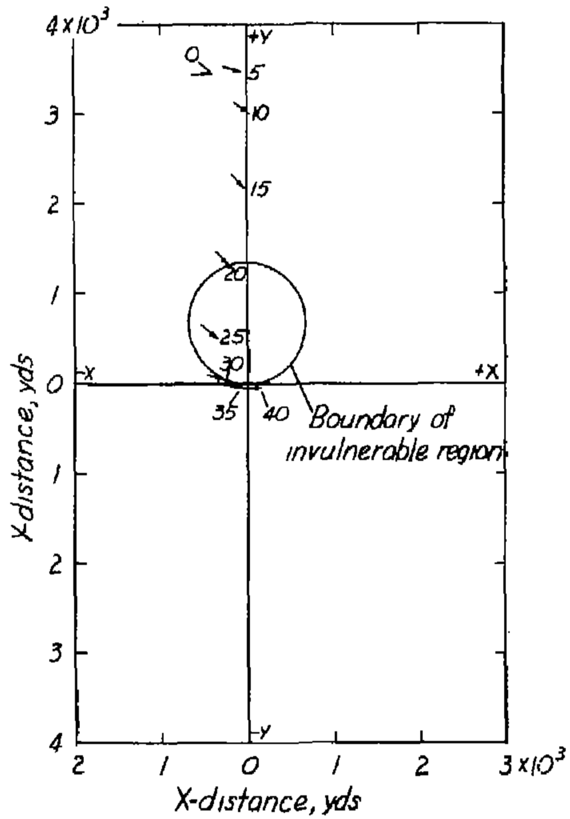
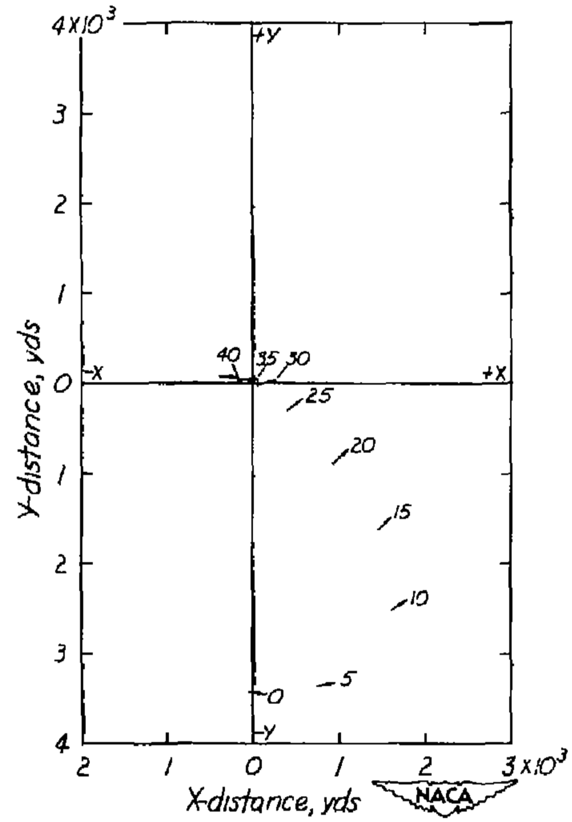
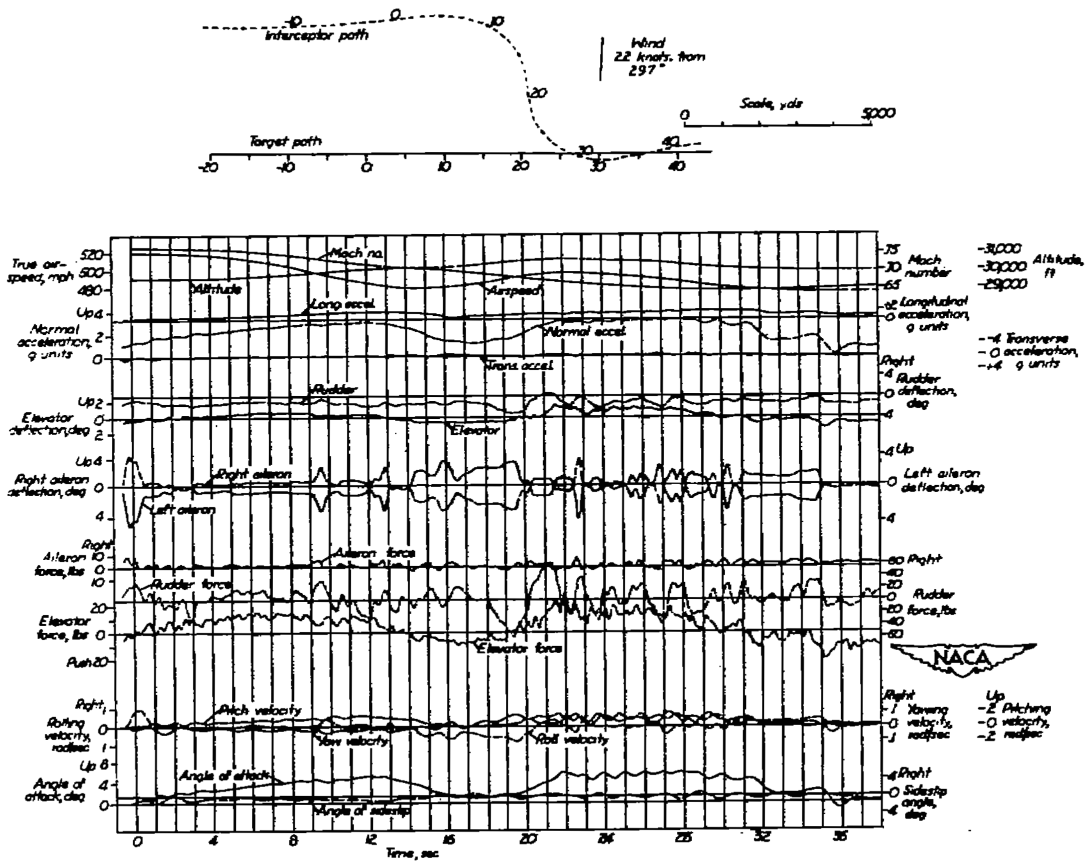


(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 5.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 6.- Interceptor airplane attacking target airplane from an overtaking encounter.

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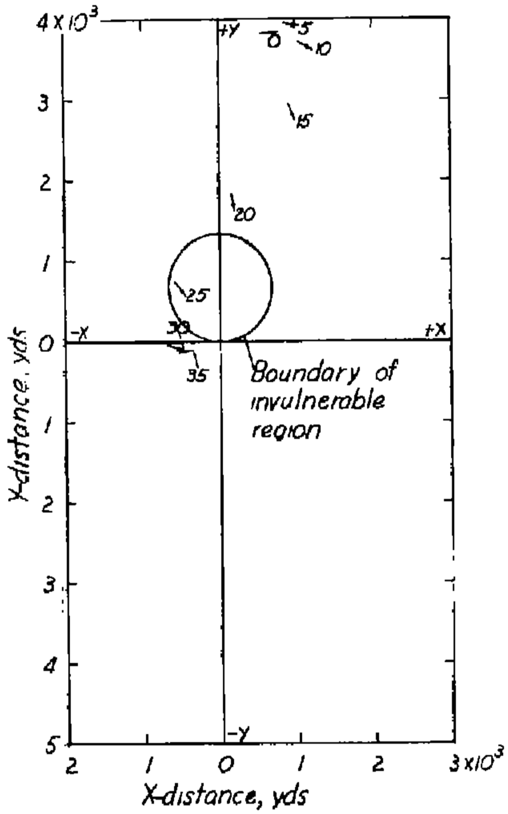
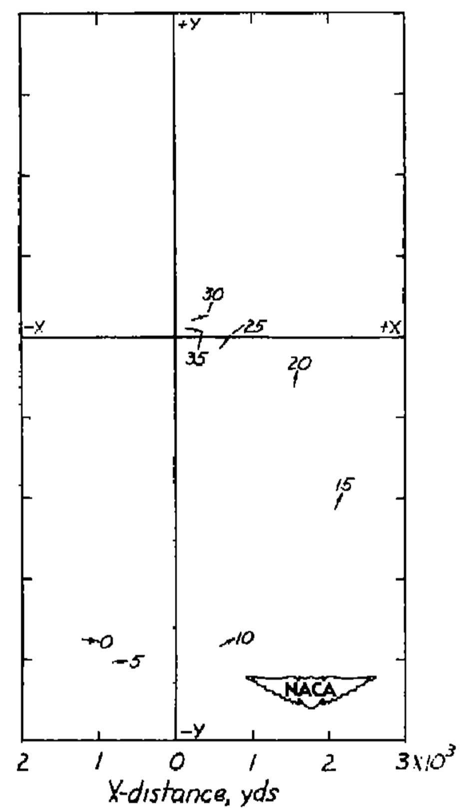
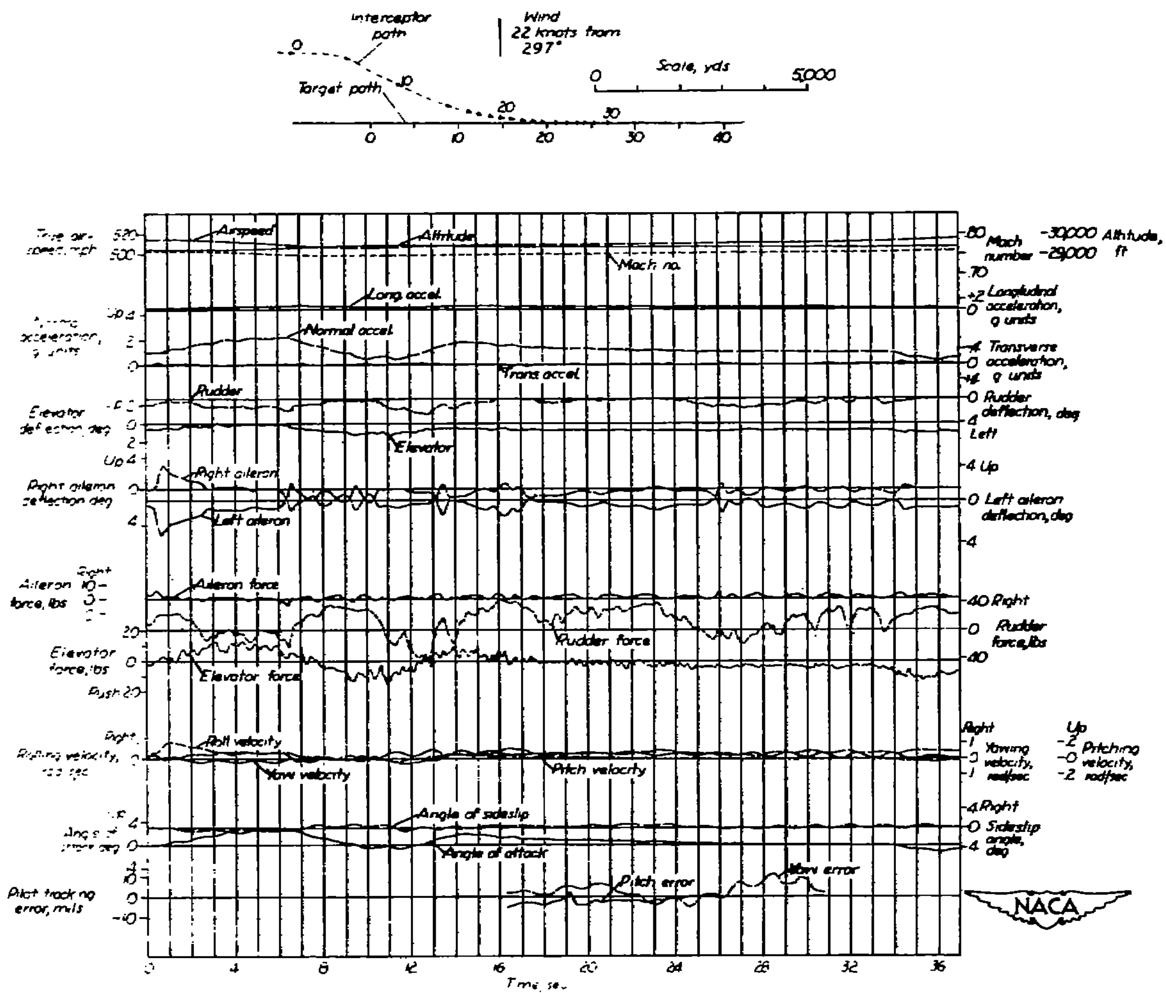


(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 6.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 7.- Interceptor airplane attacking target airplane from an overtaking encounter.

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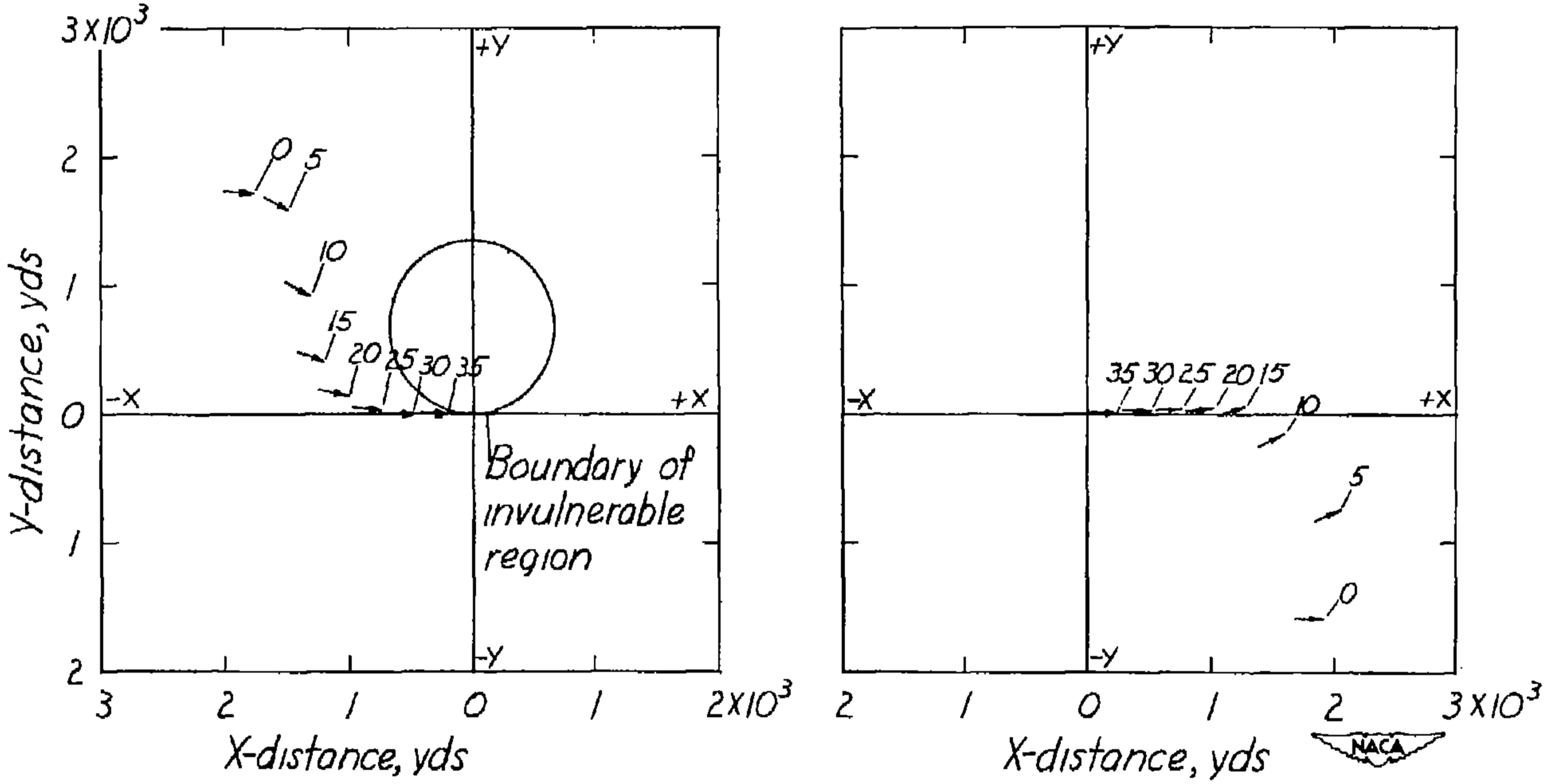
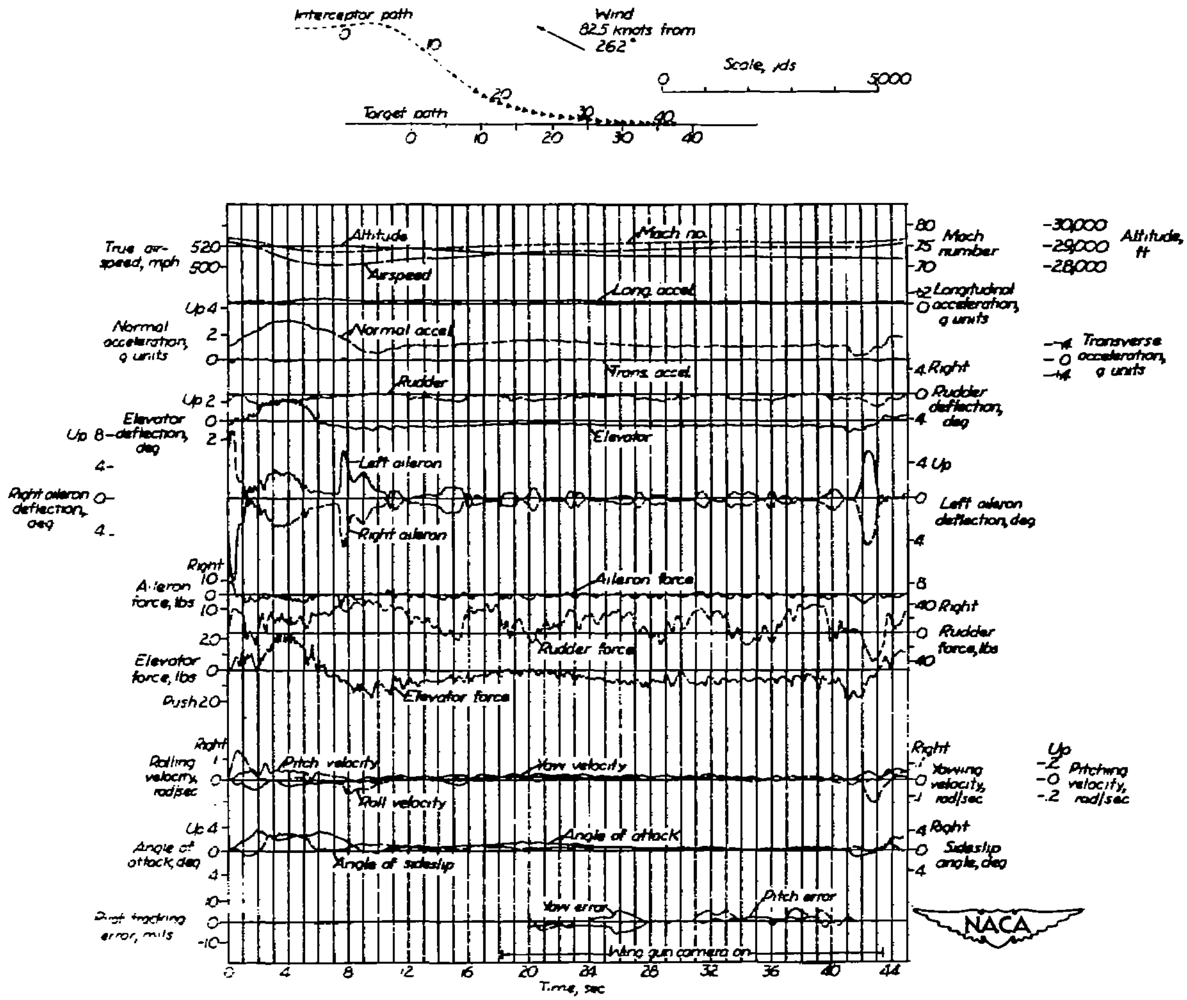


(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 7.- Concluded.

[redacted]



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 8.- Interceptor airplane attacking target airplane from an overtaking encounter.

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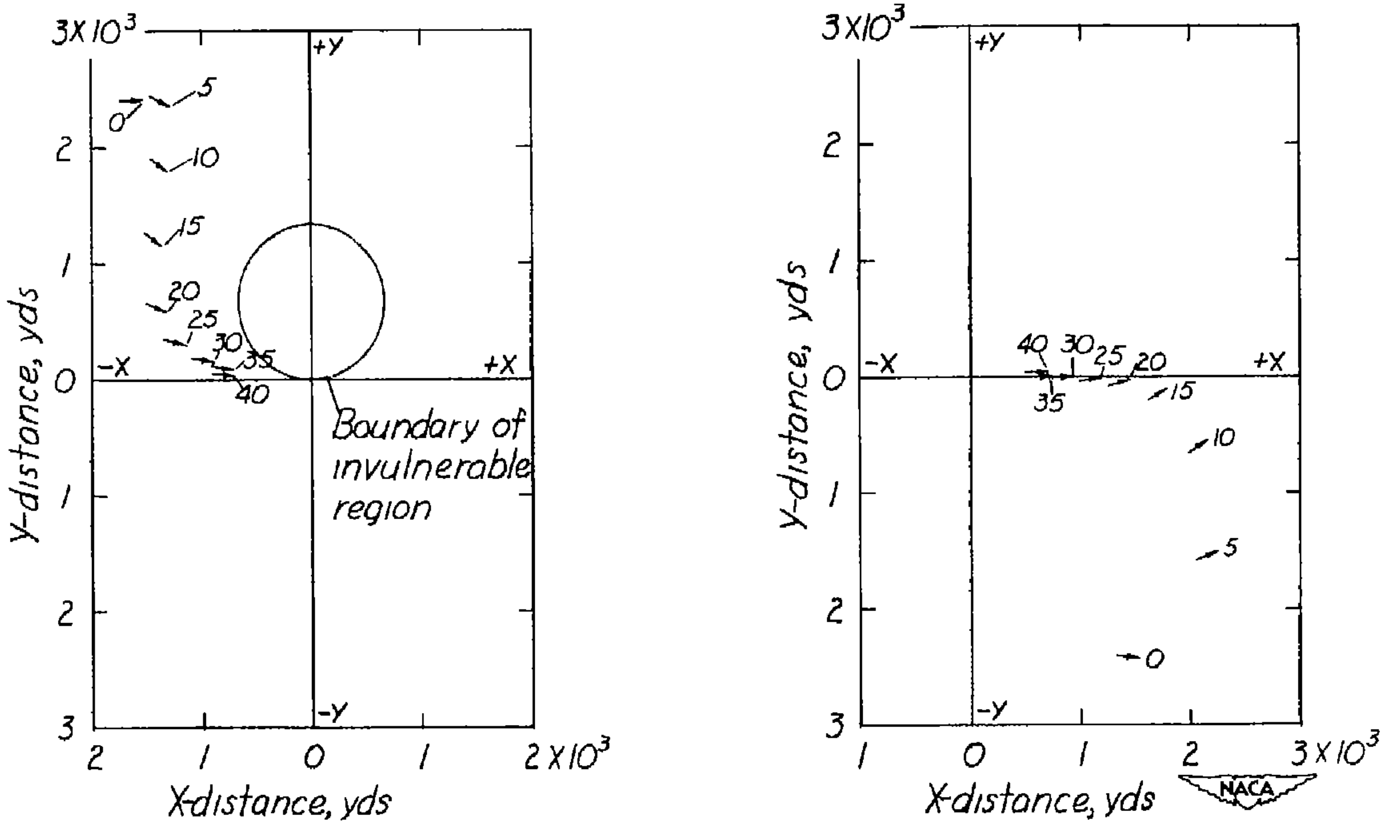
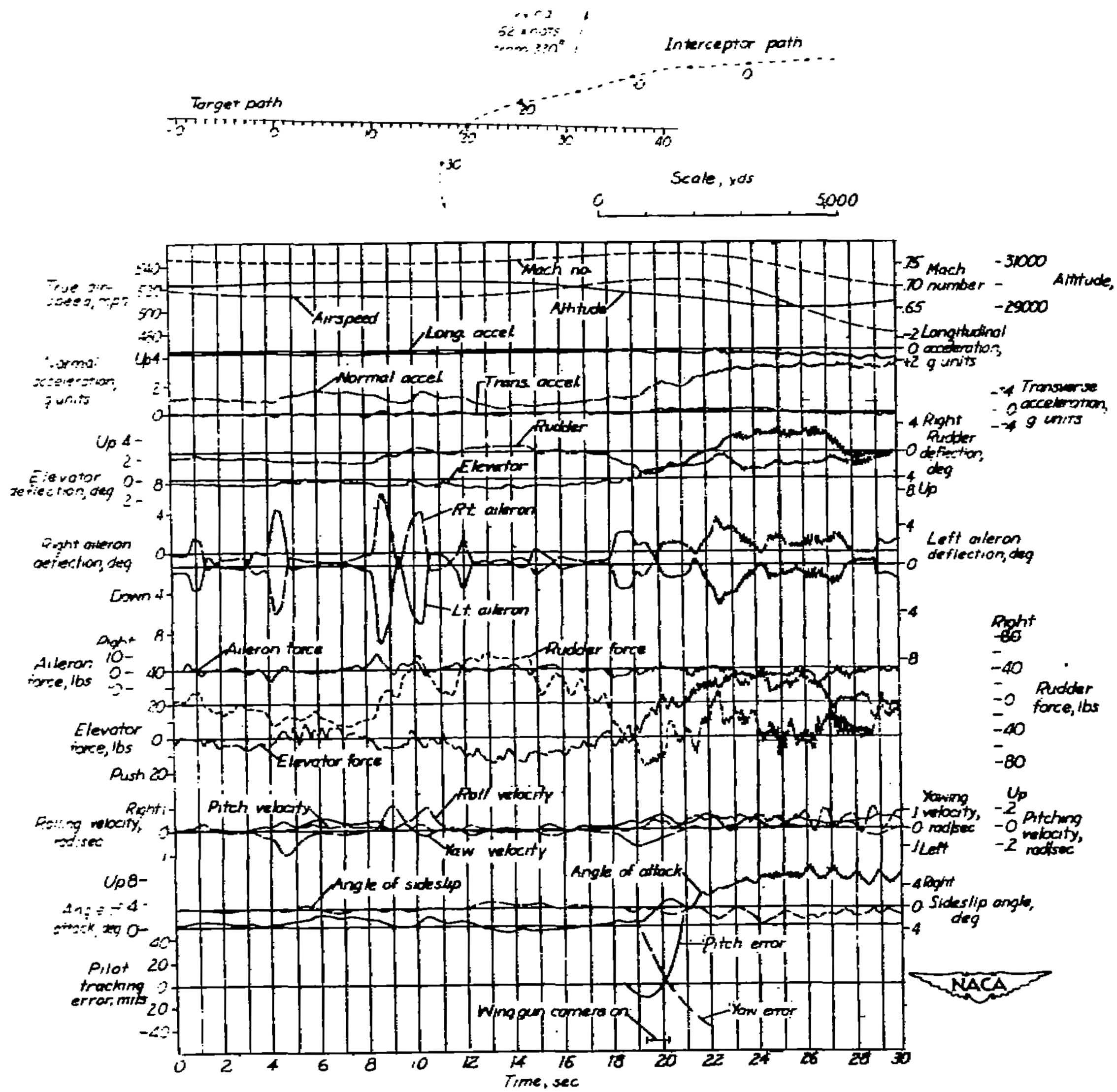


(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

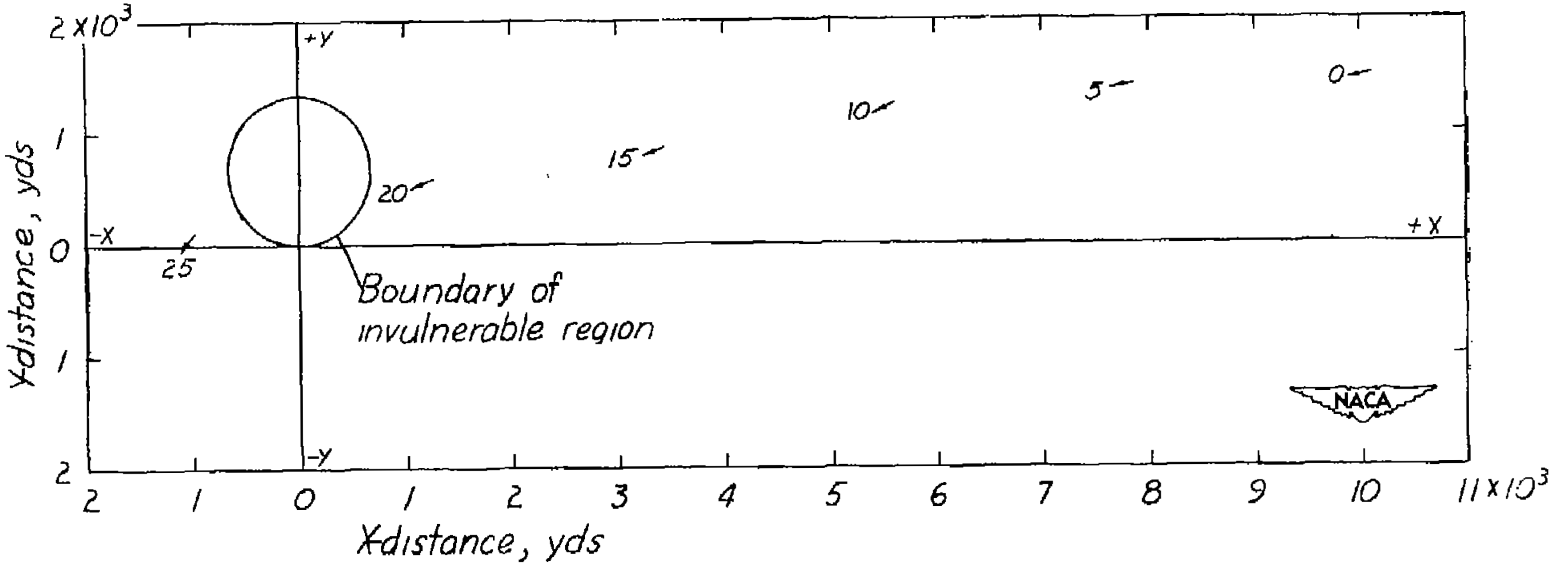
Figure 8.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 9.- Interceptor airplane attacking target airplane from a frontal encounter.

[redacted]



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 9.- Continued.

[redacted]

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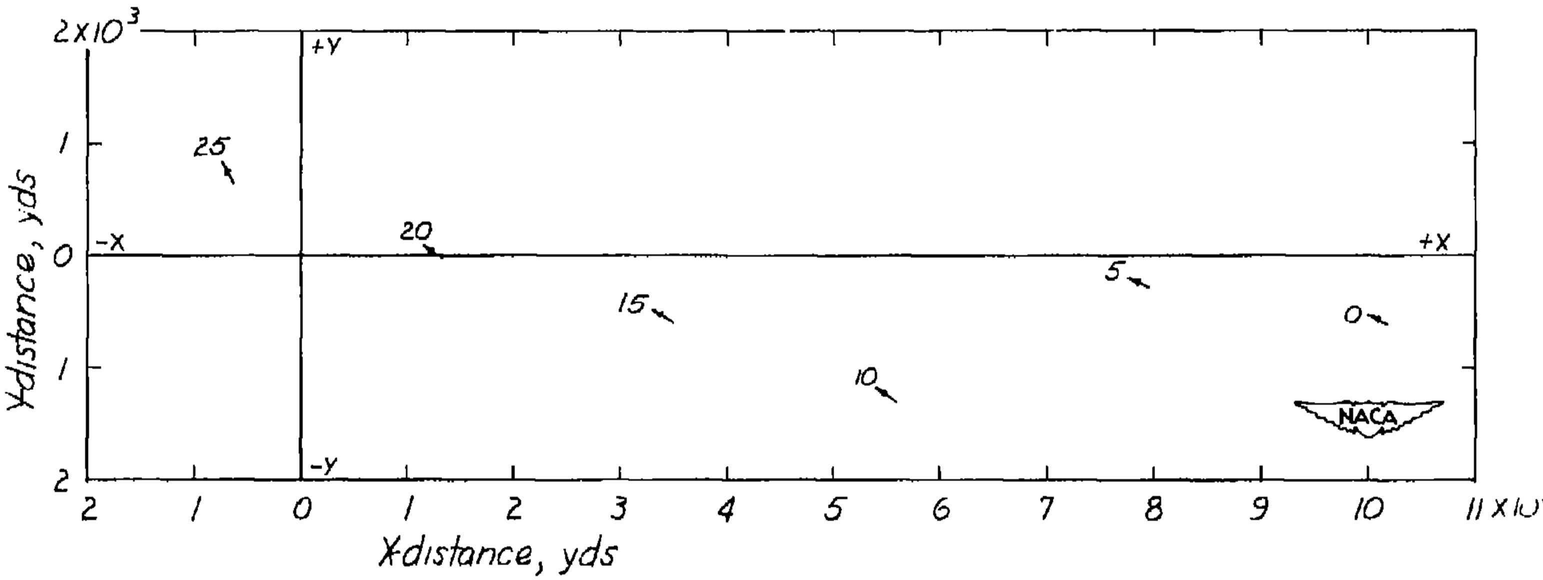
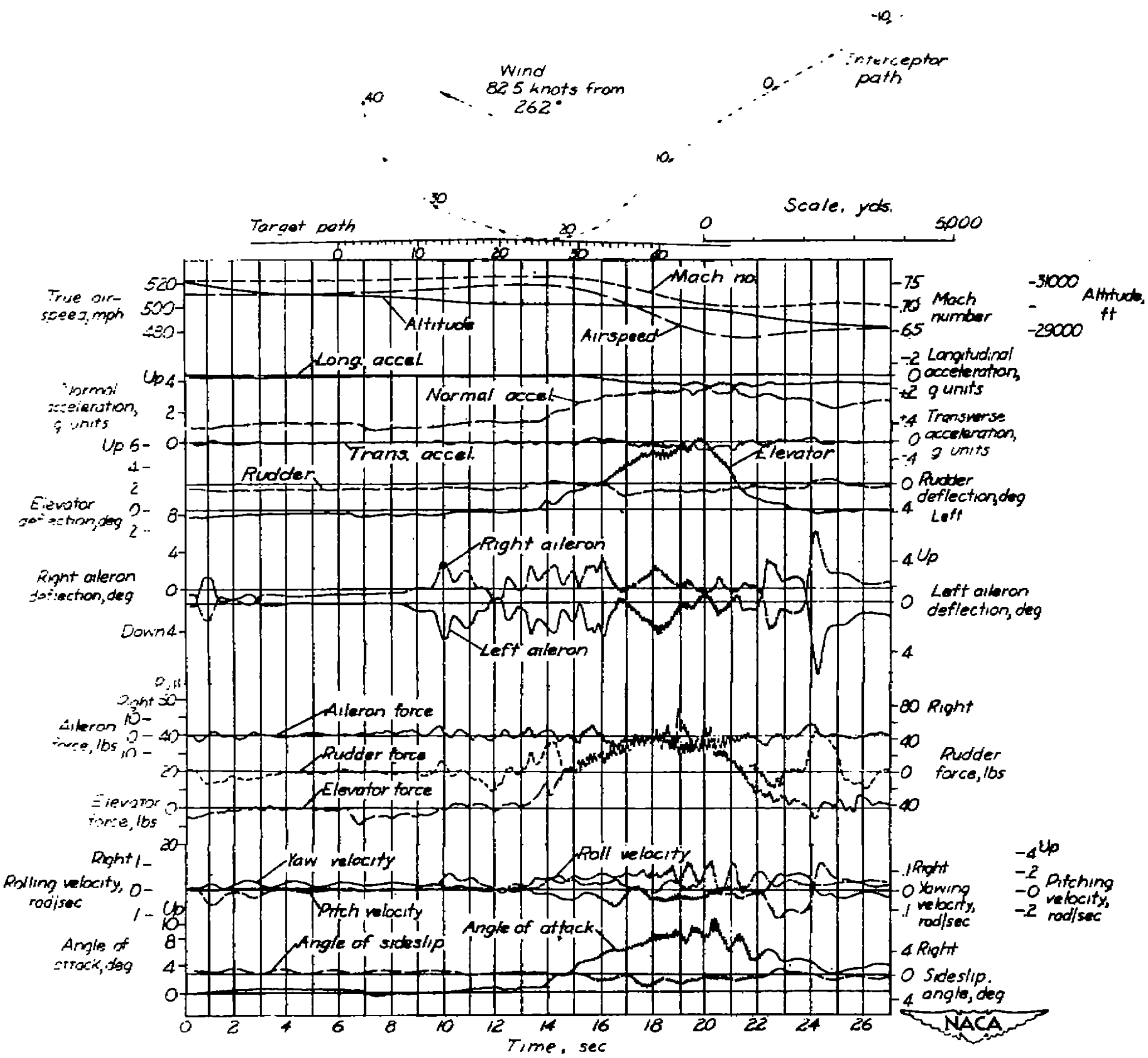


(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

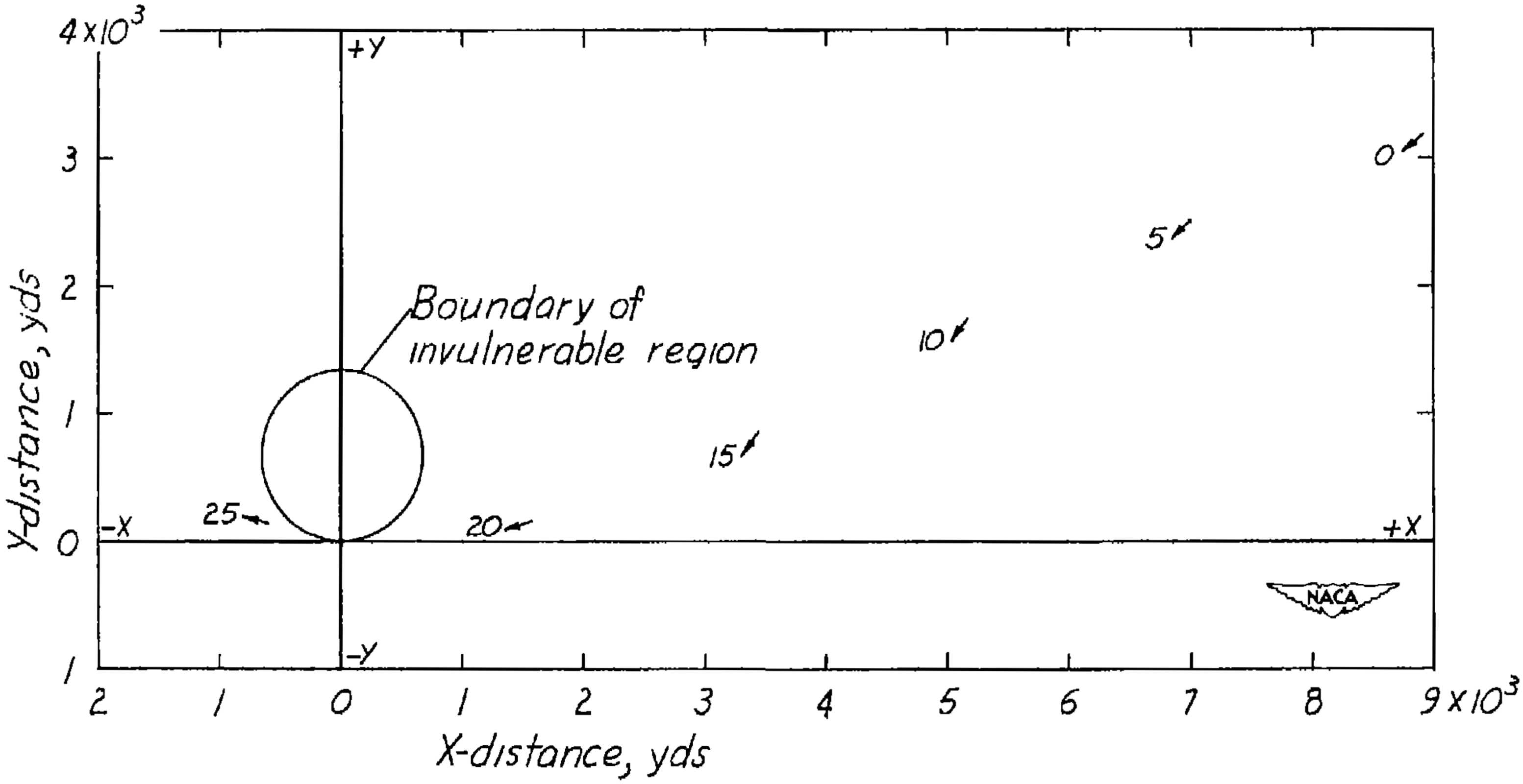
Figure 9.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 10.- Interceptor airplane attacking target airplane from a frontal encounter.

[redacted]



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 10.- Continued.

[redacted]

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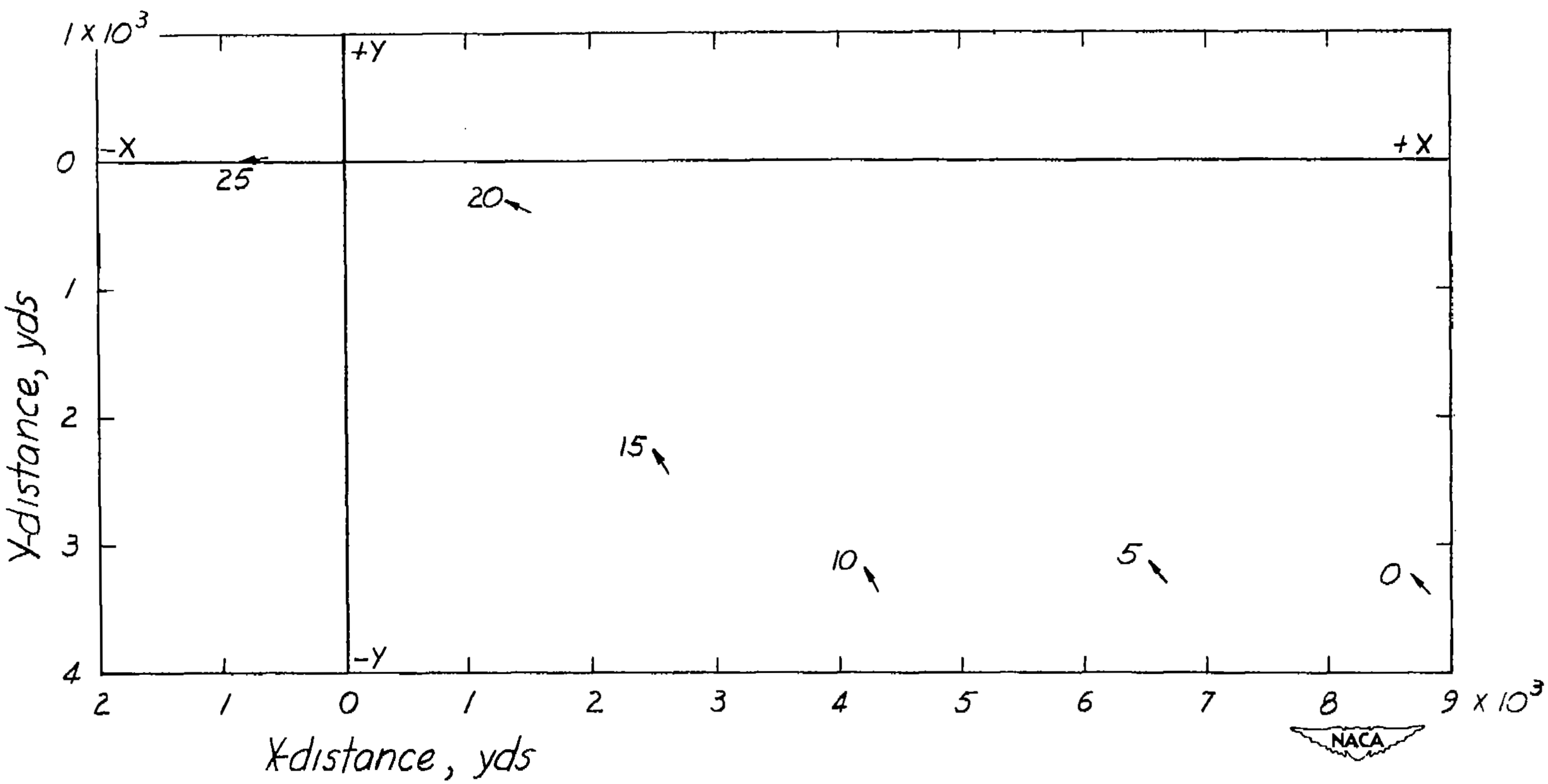
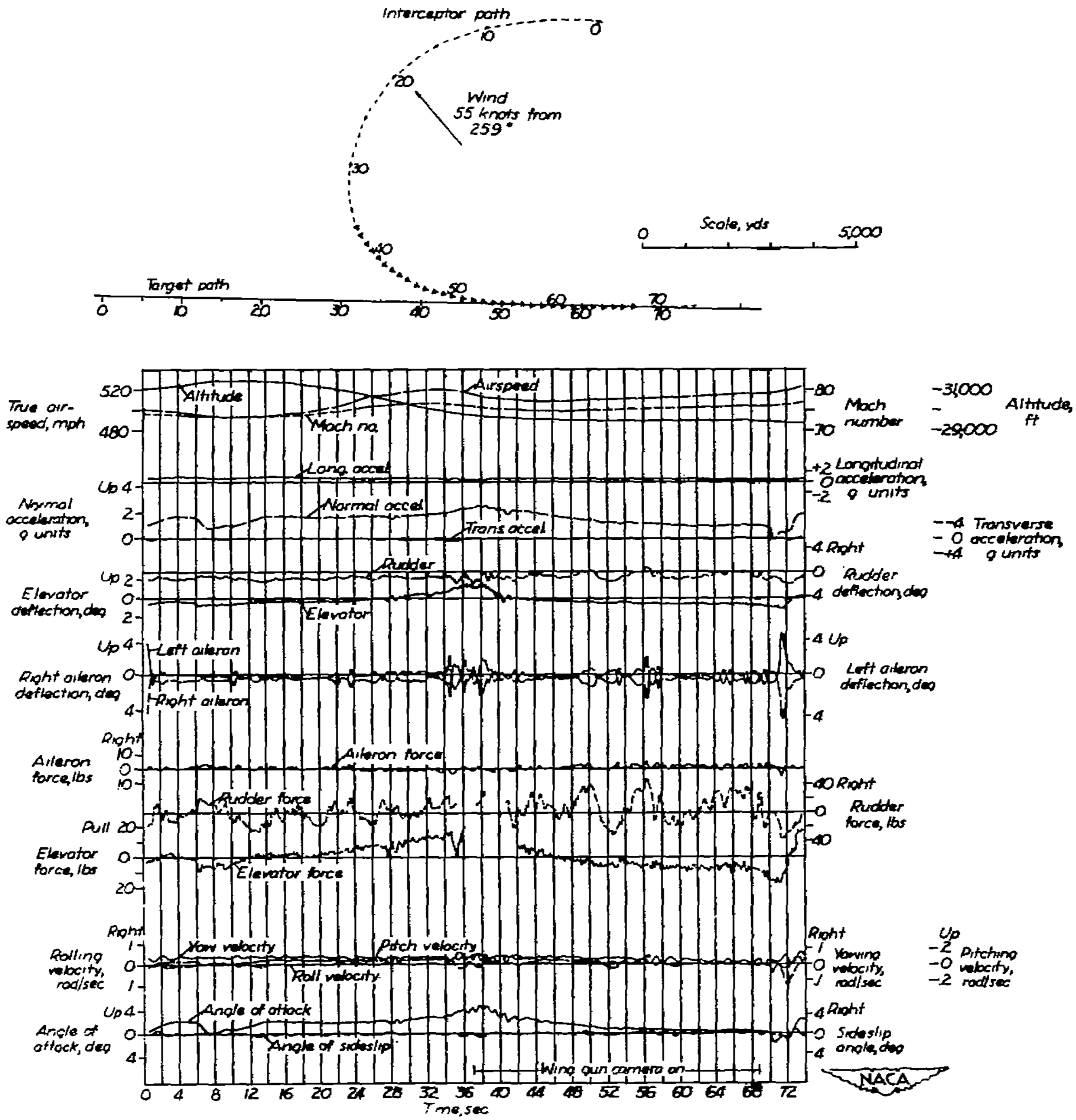


(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 10.- Concluded.

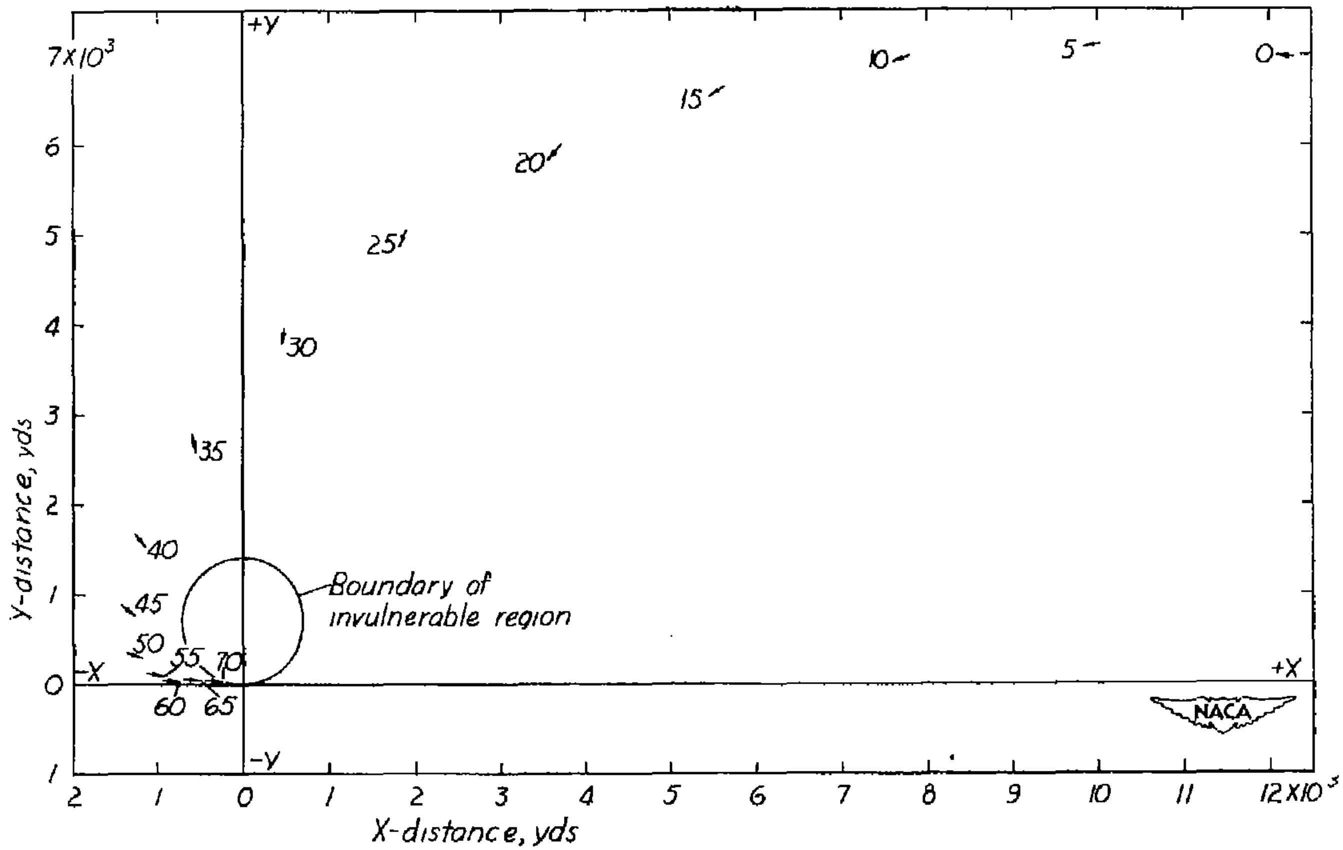


(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 11.- Interceptor airplane attacking target airplane from a frontal encounter.

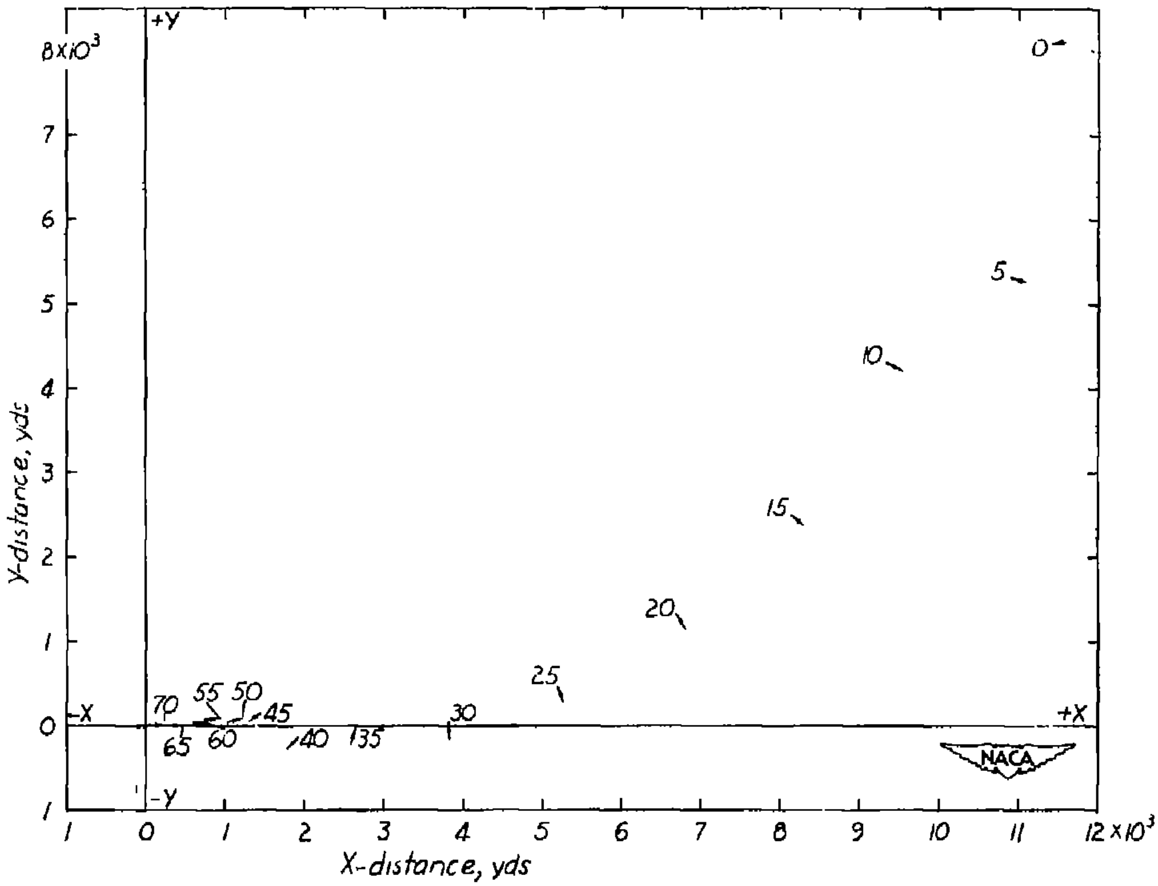
[redacted]

[redacted]



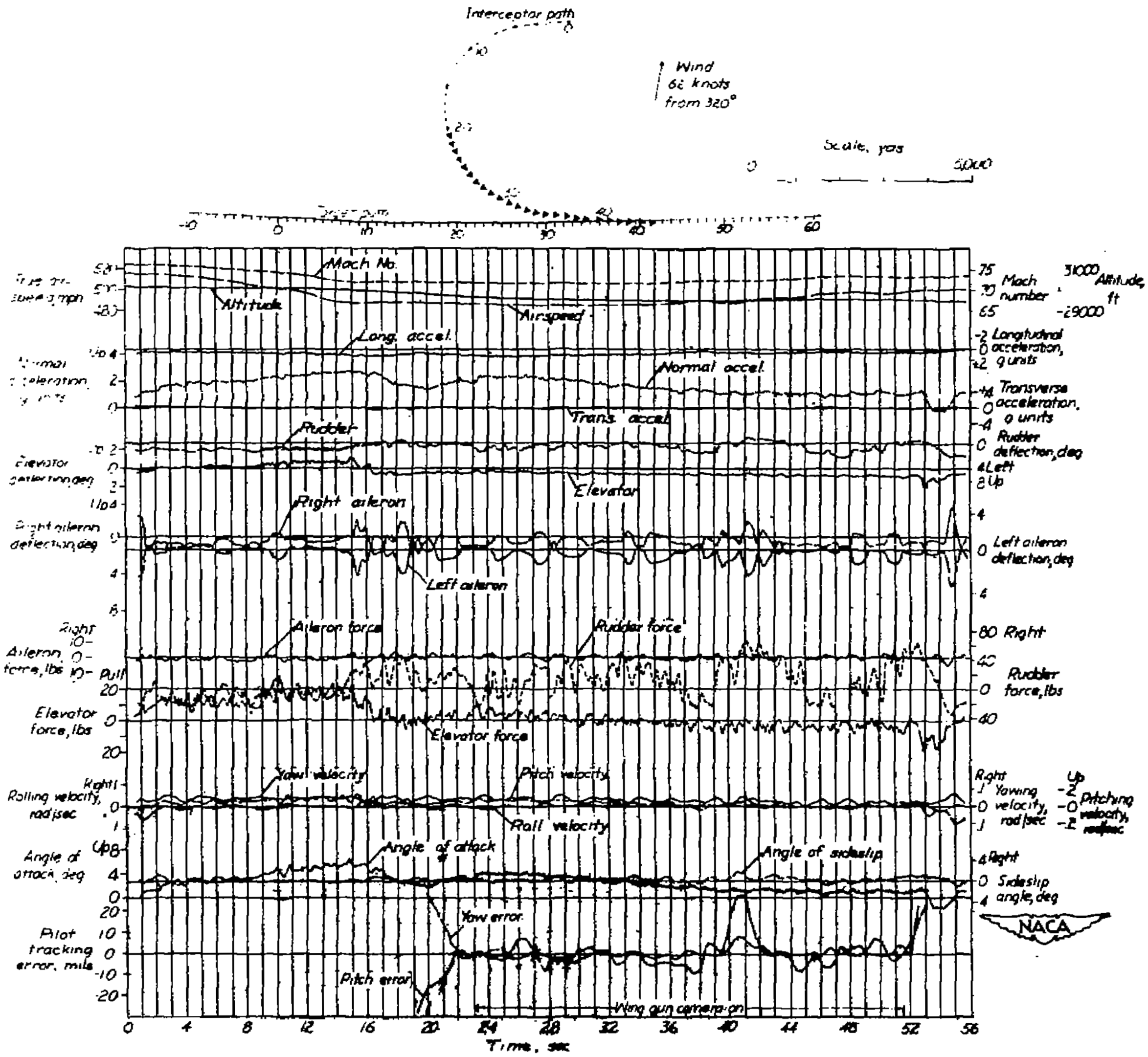
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 11.- Continued.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

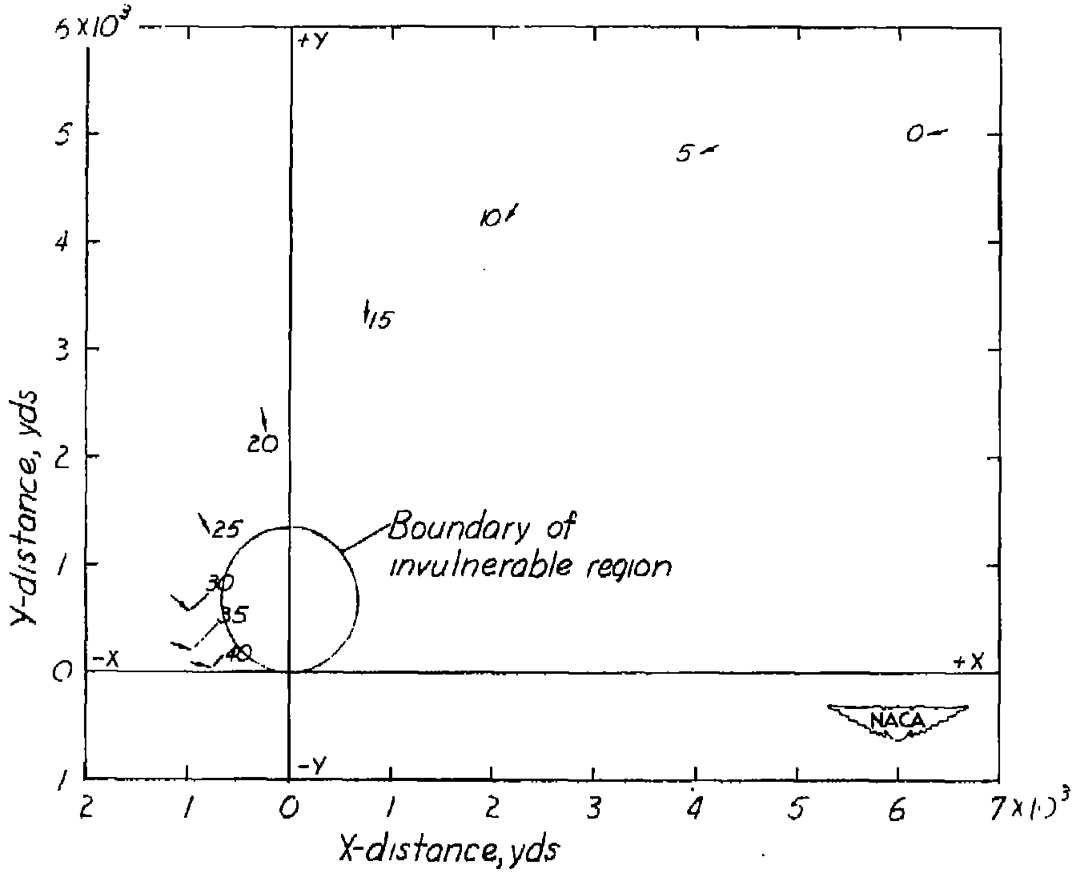
Figure 11.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 12.- Interceptor airplane attacking target airplane from a frontal encounter.

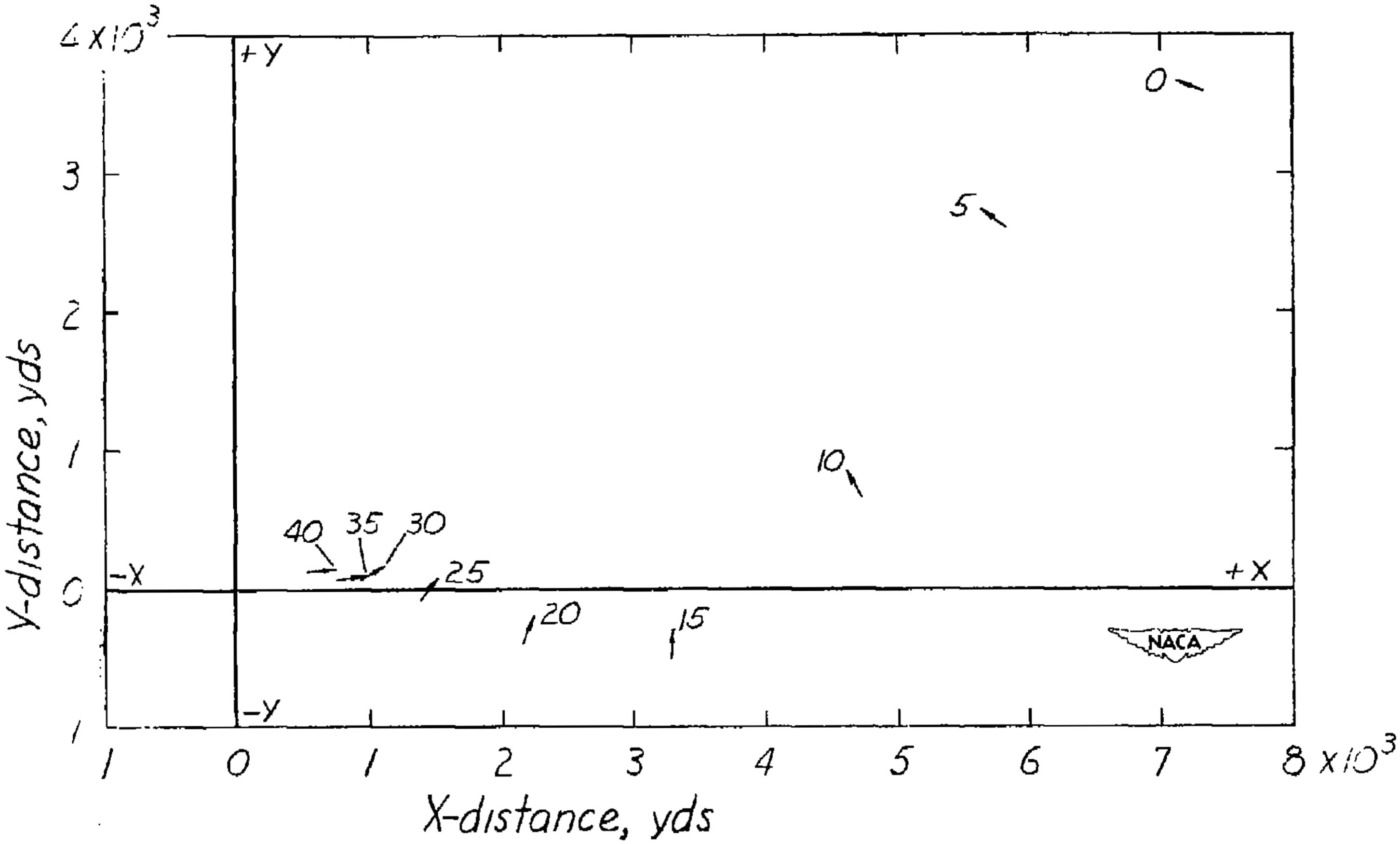
[redacted]



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 12.- Continued.

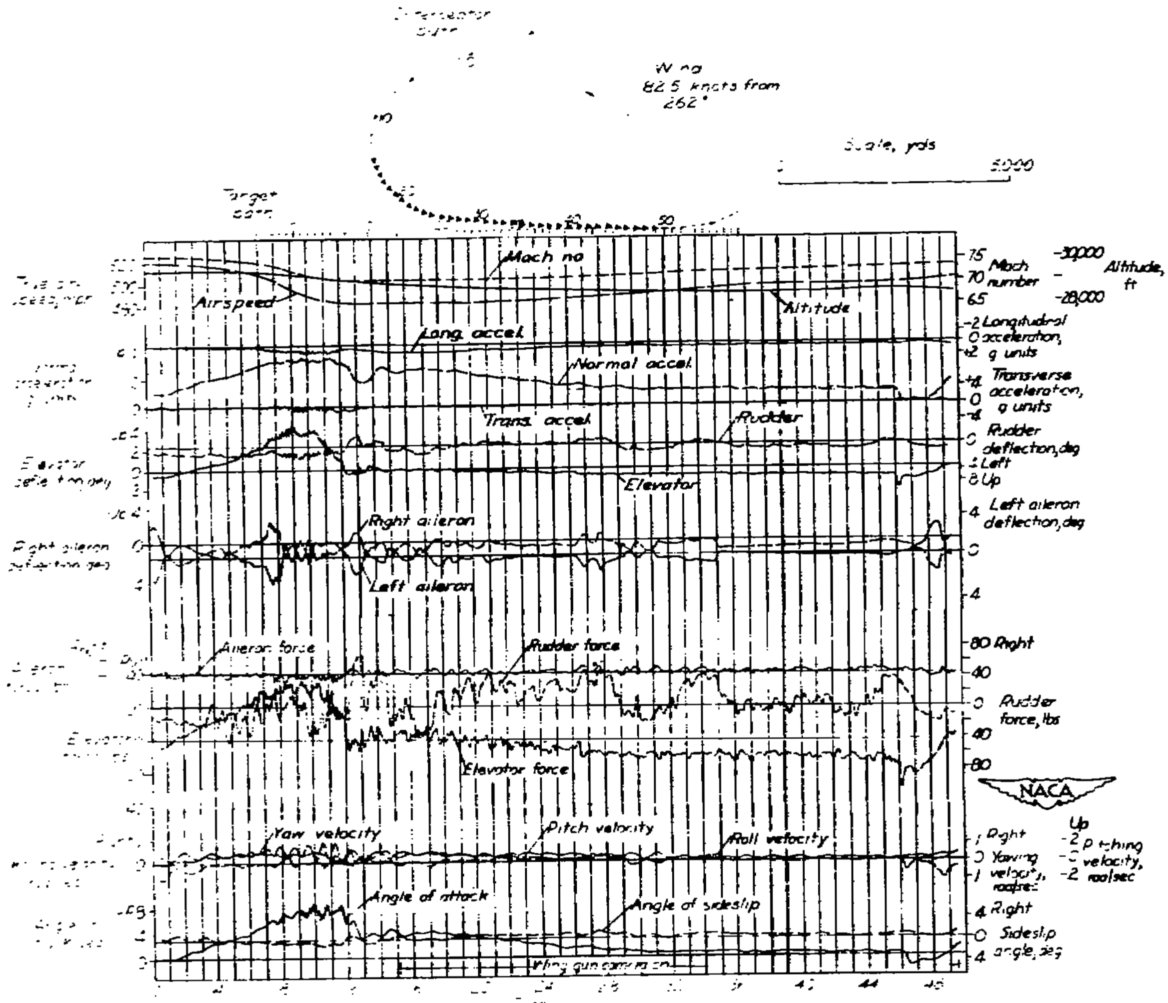
[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 12.- Concluded.

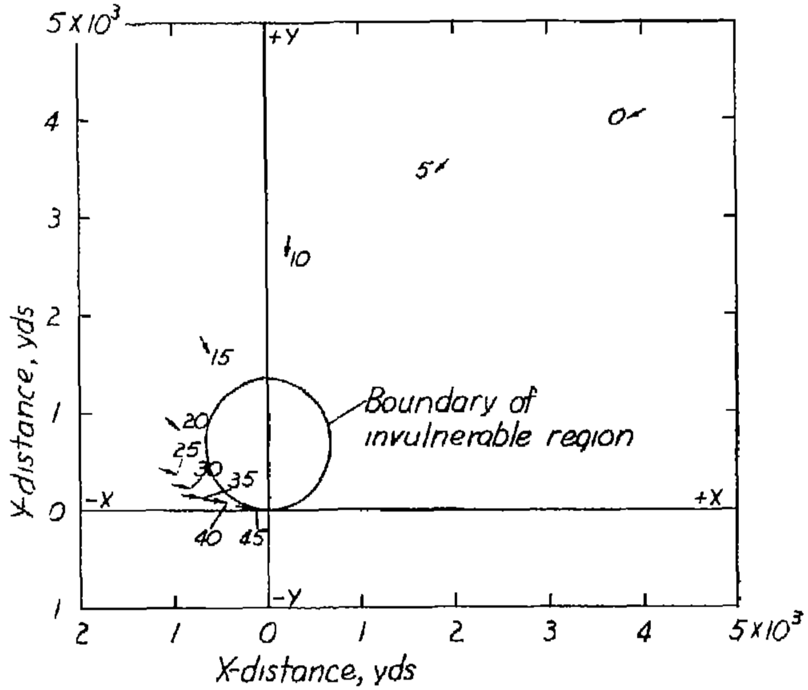
[redacted]



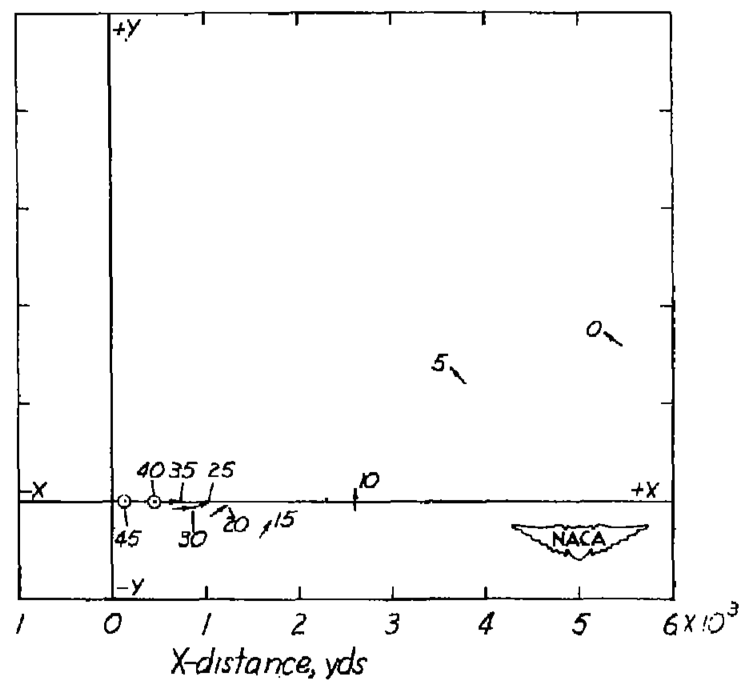
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 13.- Interceptor airplane attacking target airplane from a frontal encounter.

[redacted]



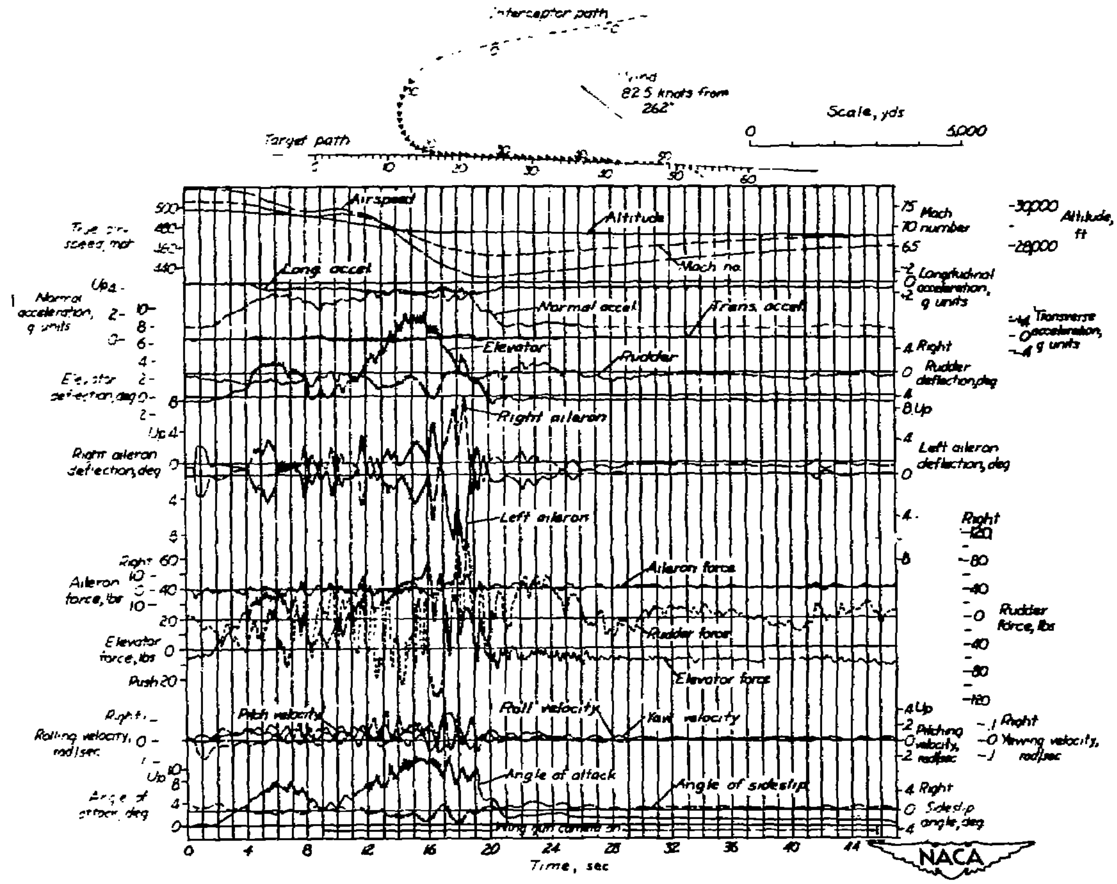
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 13.- Concluded.

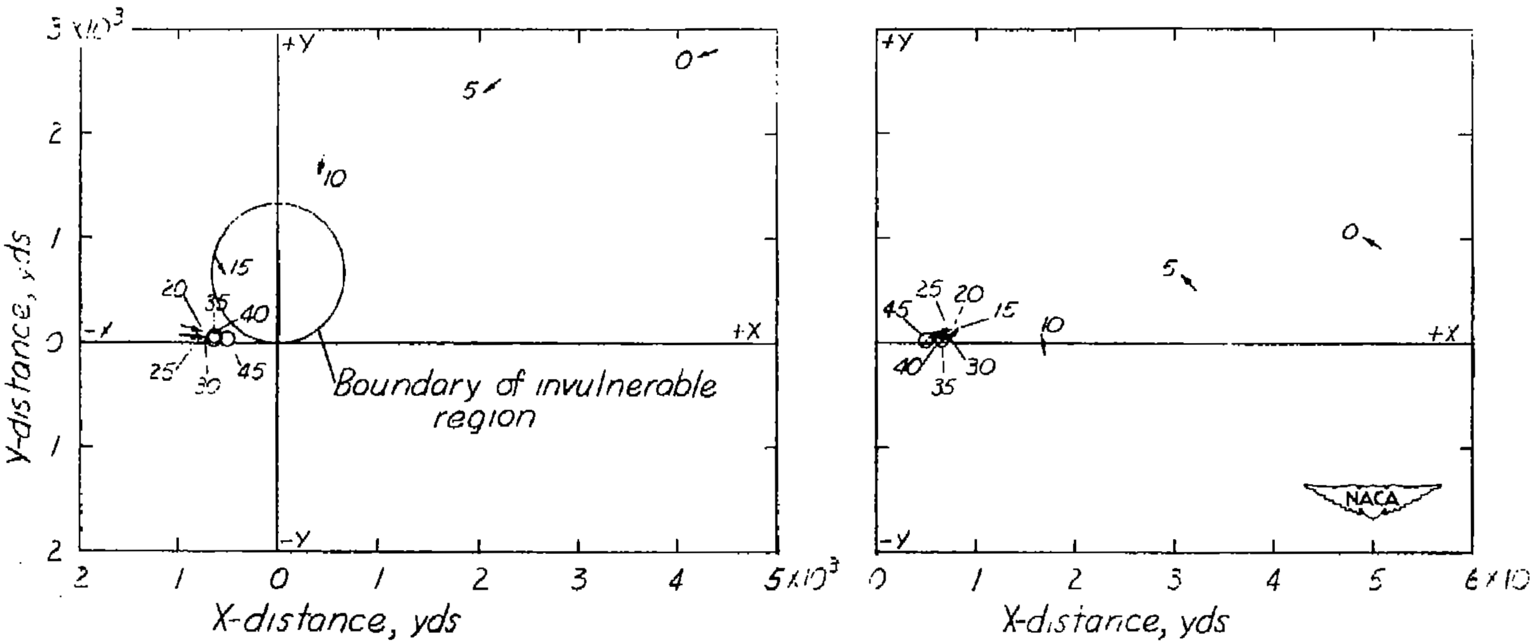
[redacted]



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 14.- Interceptor airplane attacking target airplane from a frontal encounter.

[redacted]

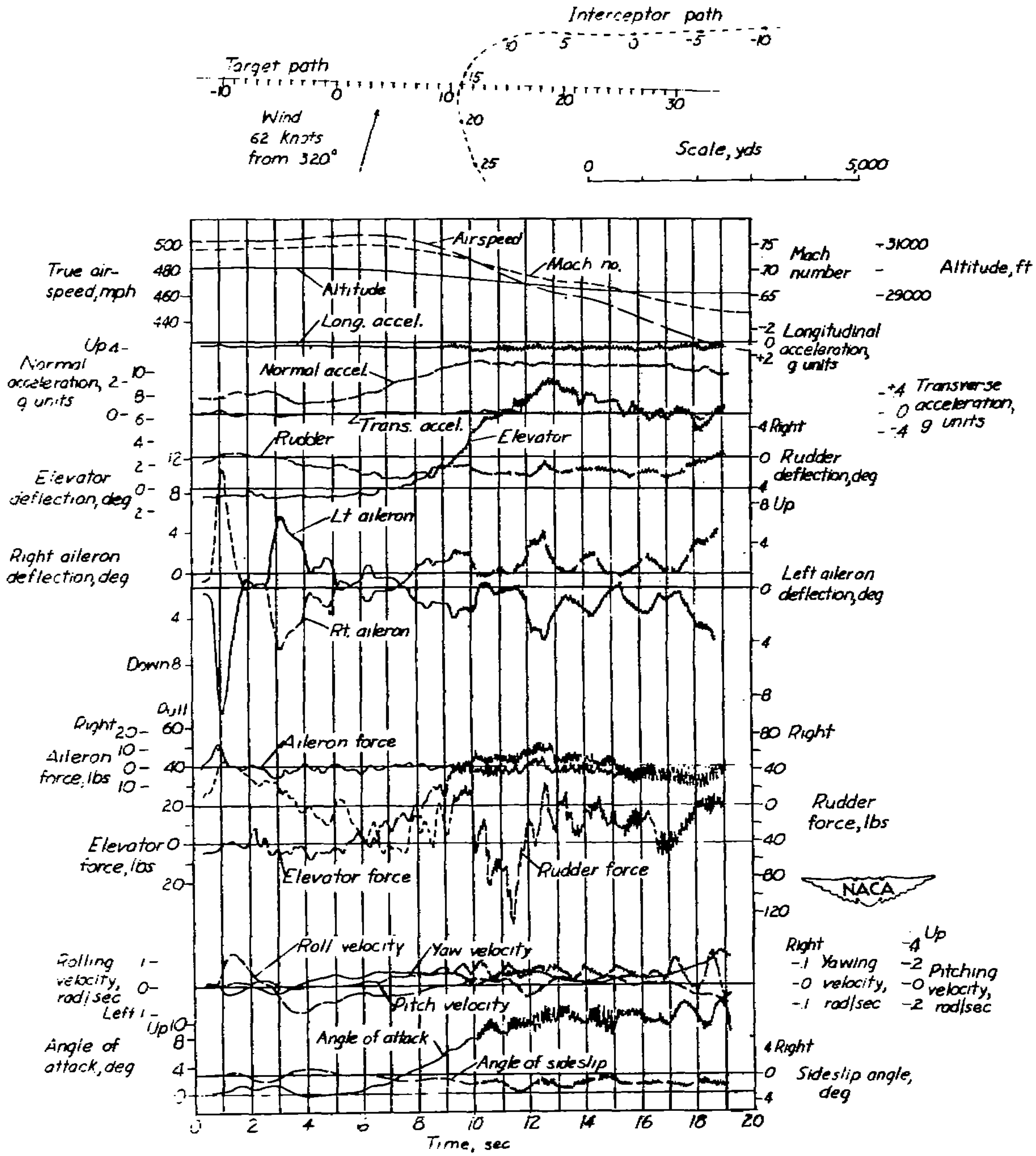


(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 14.- Concluded.

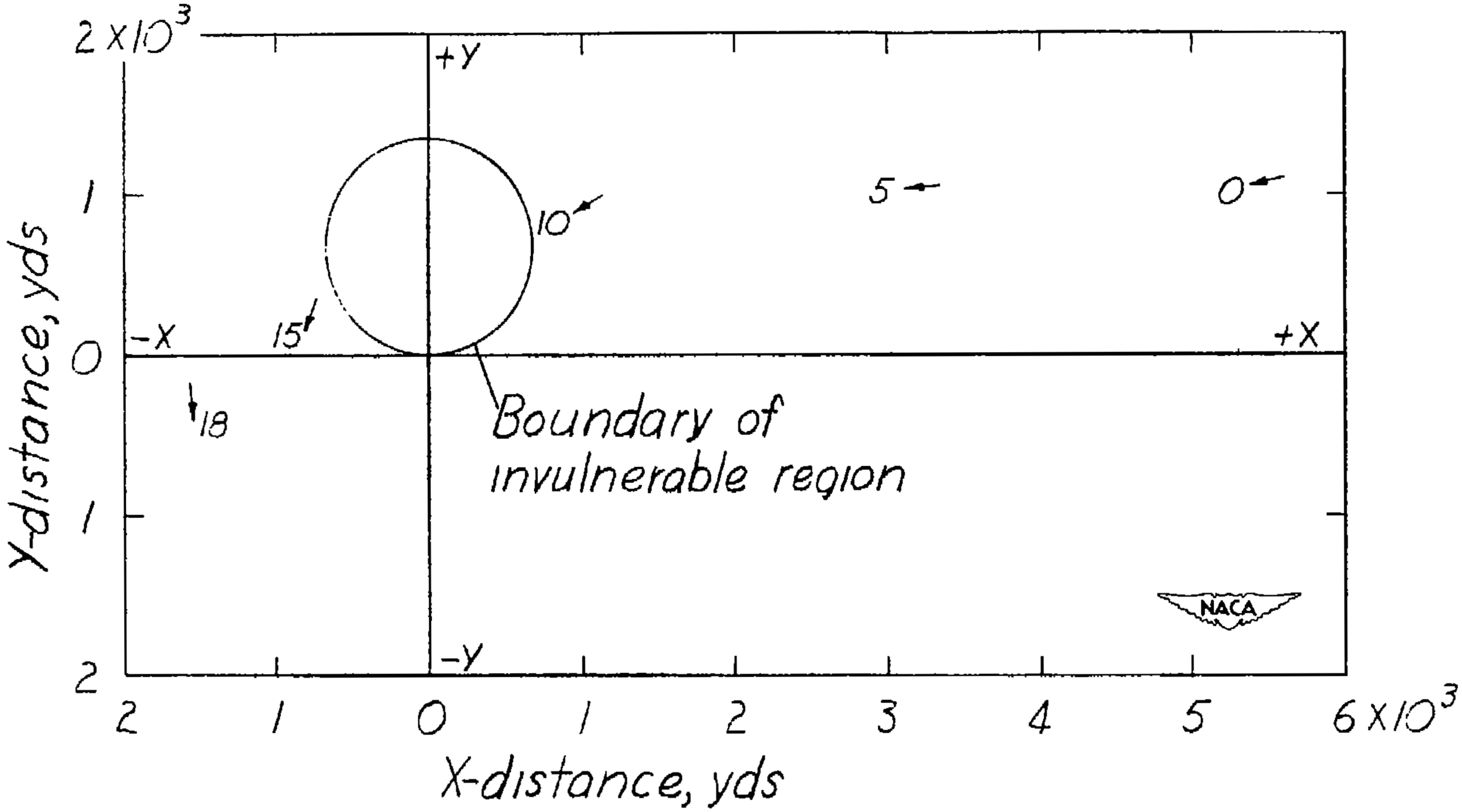
[redacted]



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 15.- Interceptor airplane attacking target airplane from a frontal encounter.

[redacted]

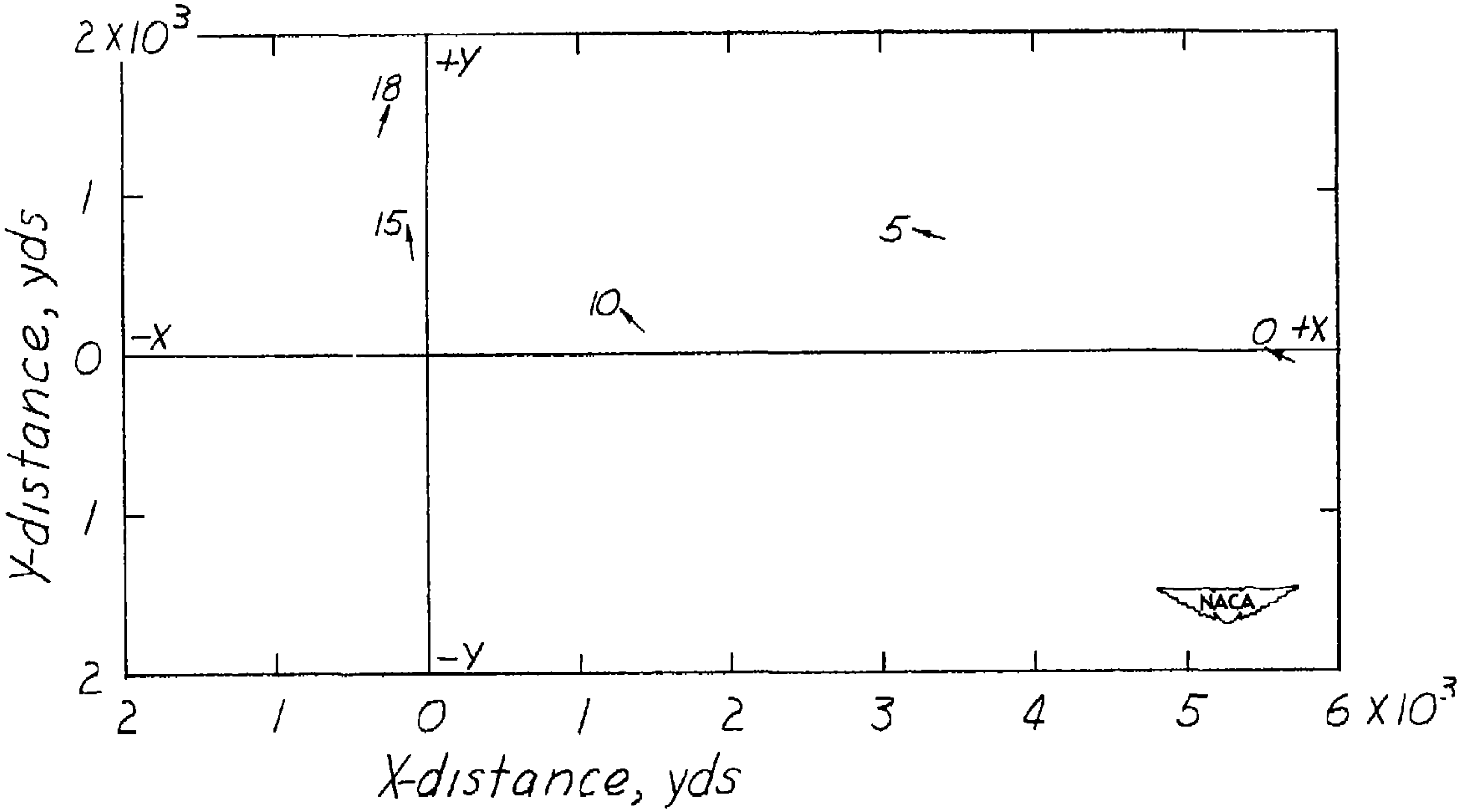


[redacted]

(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

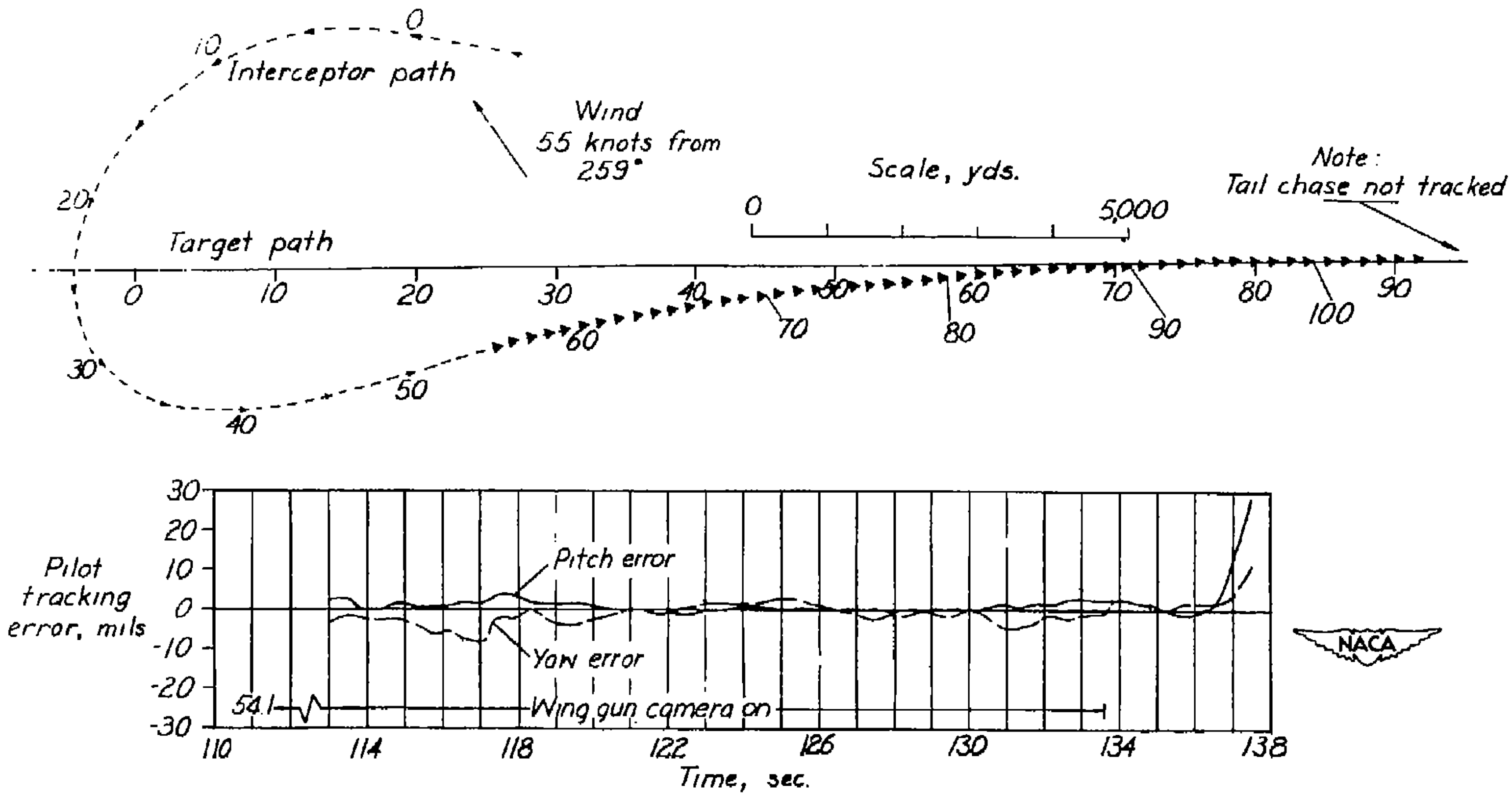
Figure 15.- Continued.

[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

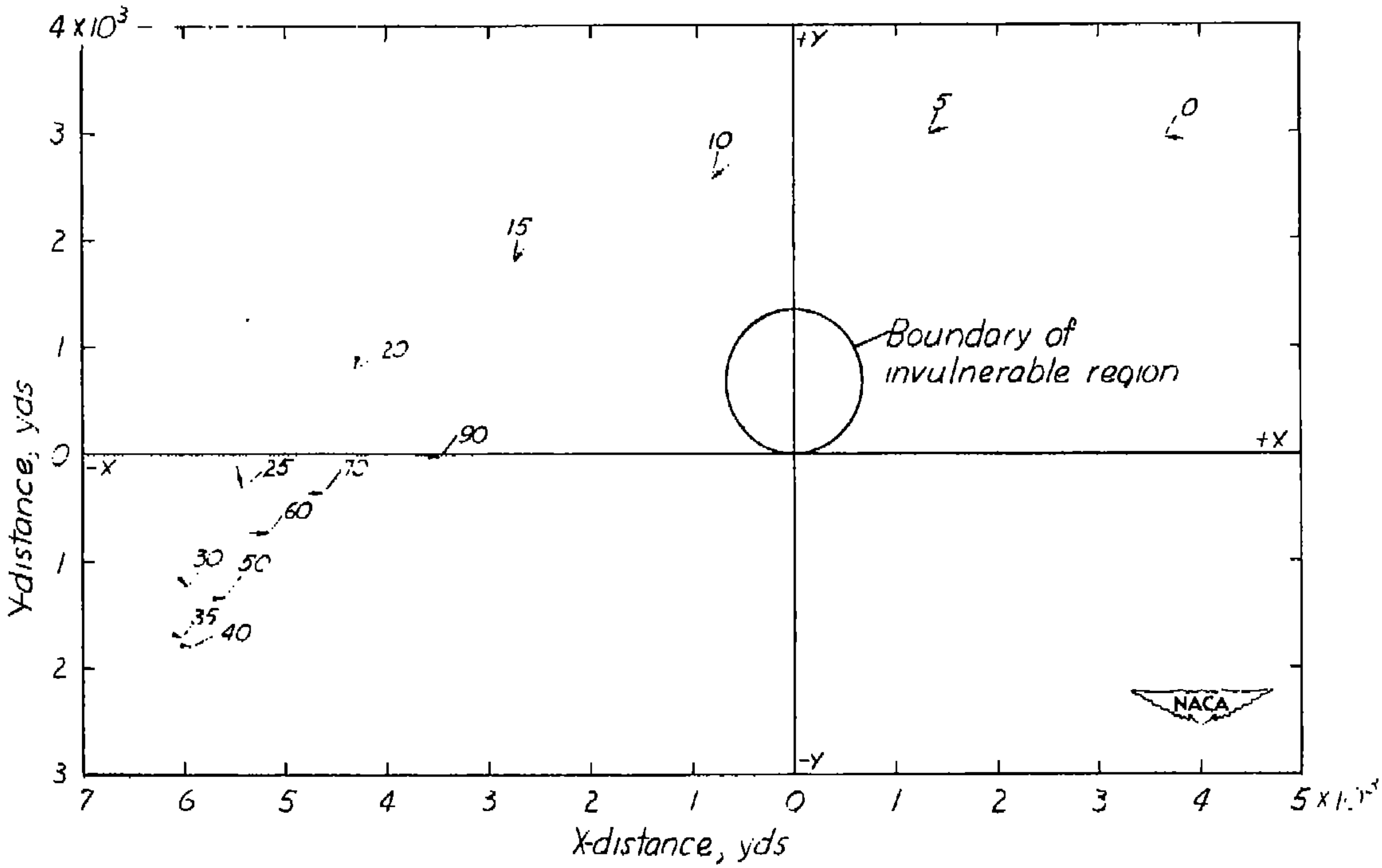
Figure 15.- Concluded.



(a) Time history of tracking-error variation recorded in the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 16.- Interceptor airplane attacking target airplane from a frontal encounter.

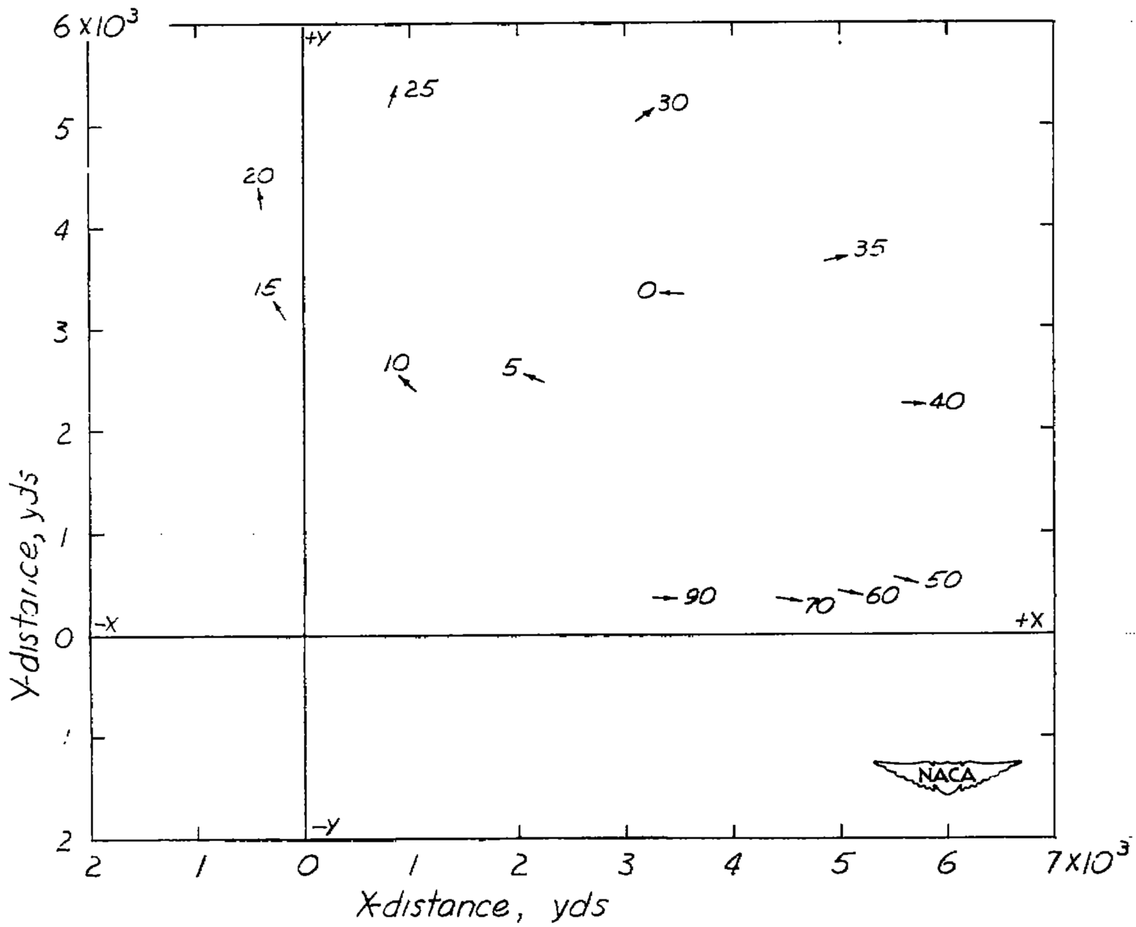
[redacted]



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 16.- Continued.

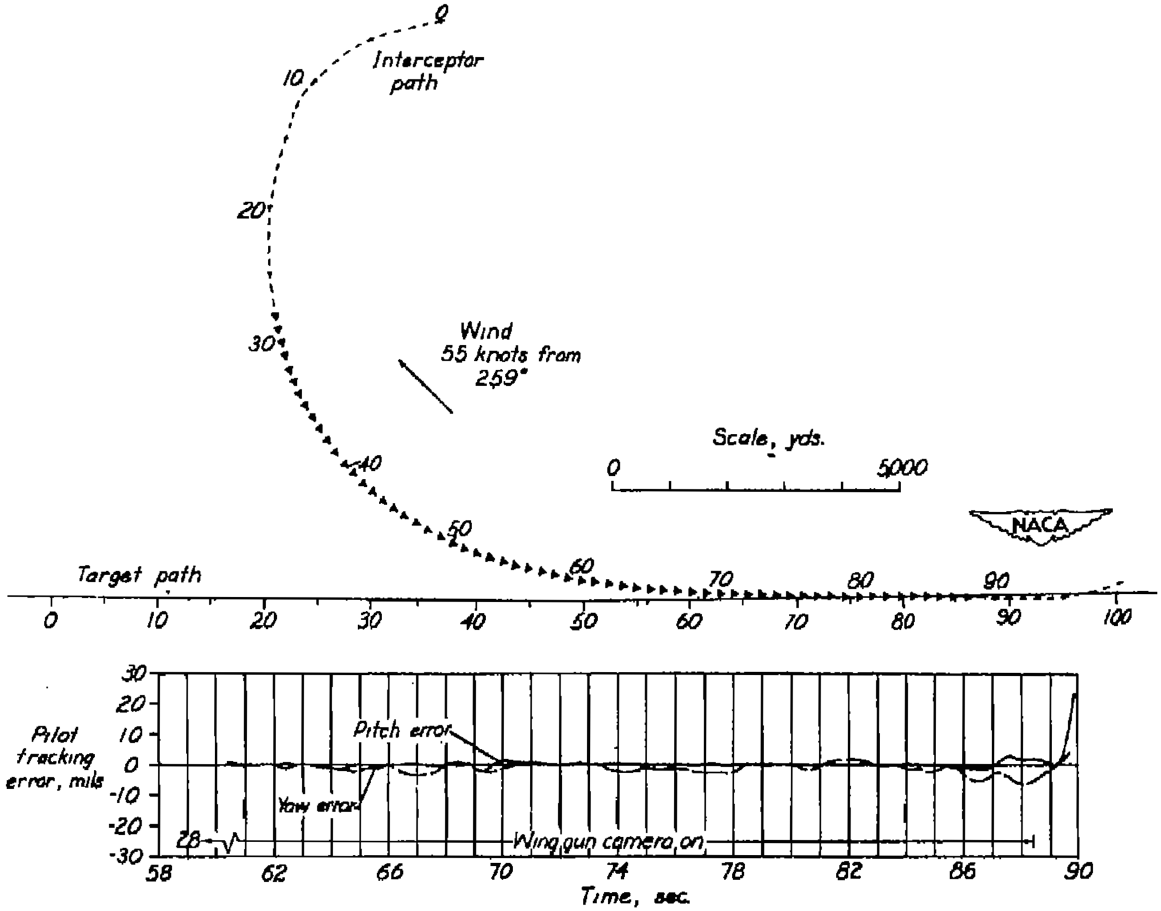
[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 16.- Concluded.

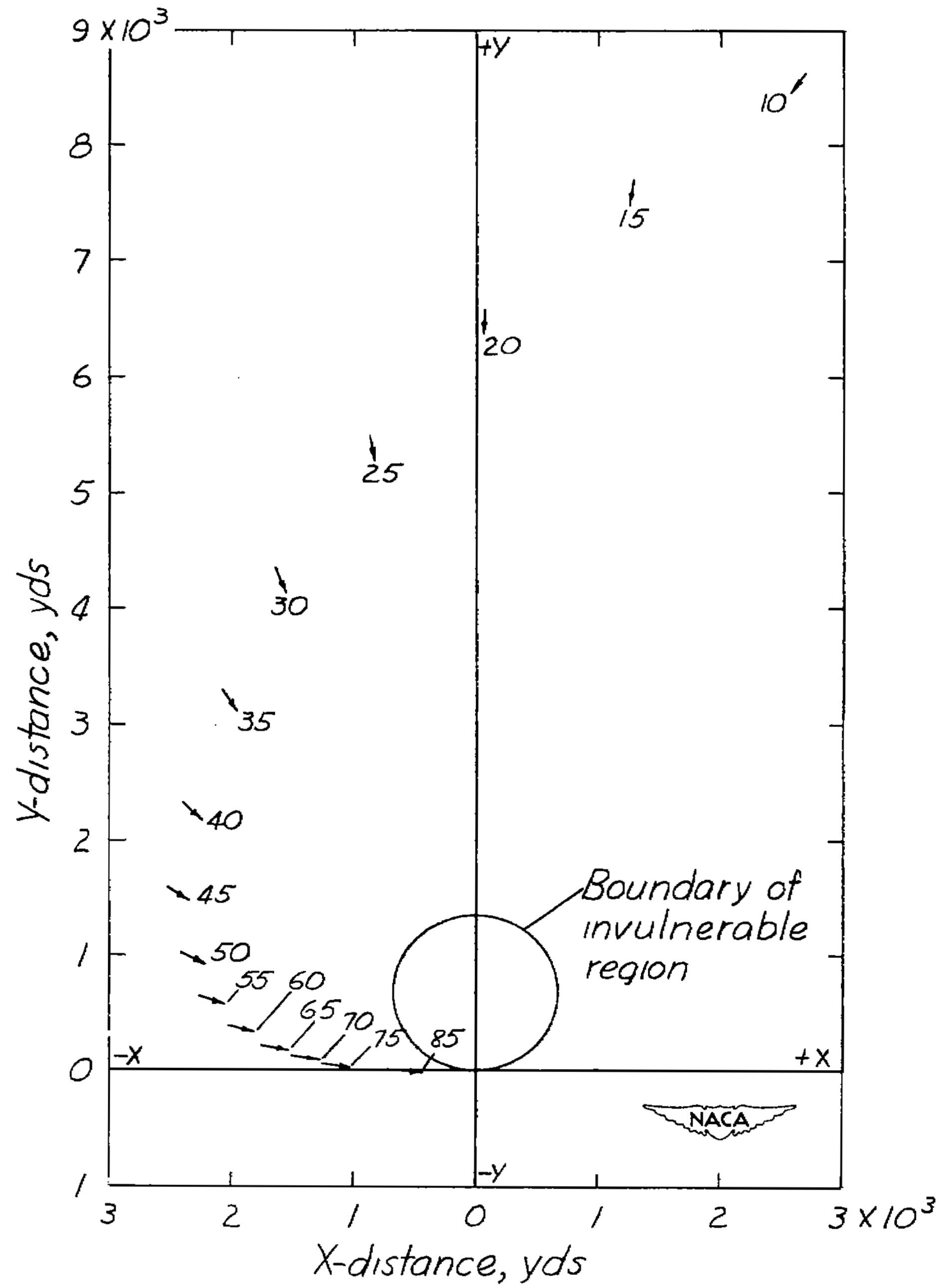
[redacted]



(a) Time history of tracking-error variation recorded in the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 17.- Interceptor airplane attacking target airplane from a frontal encounter.

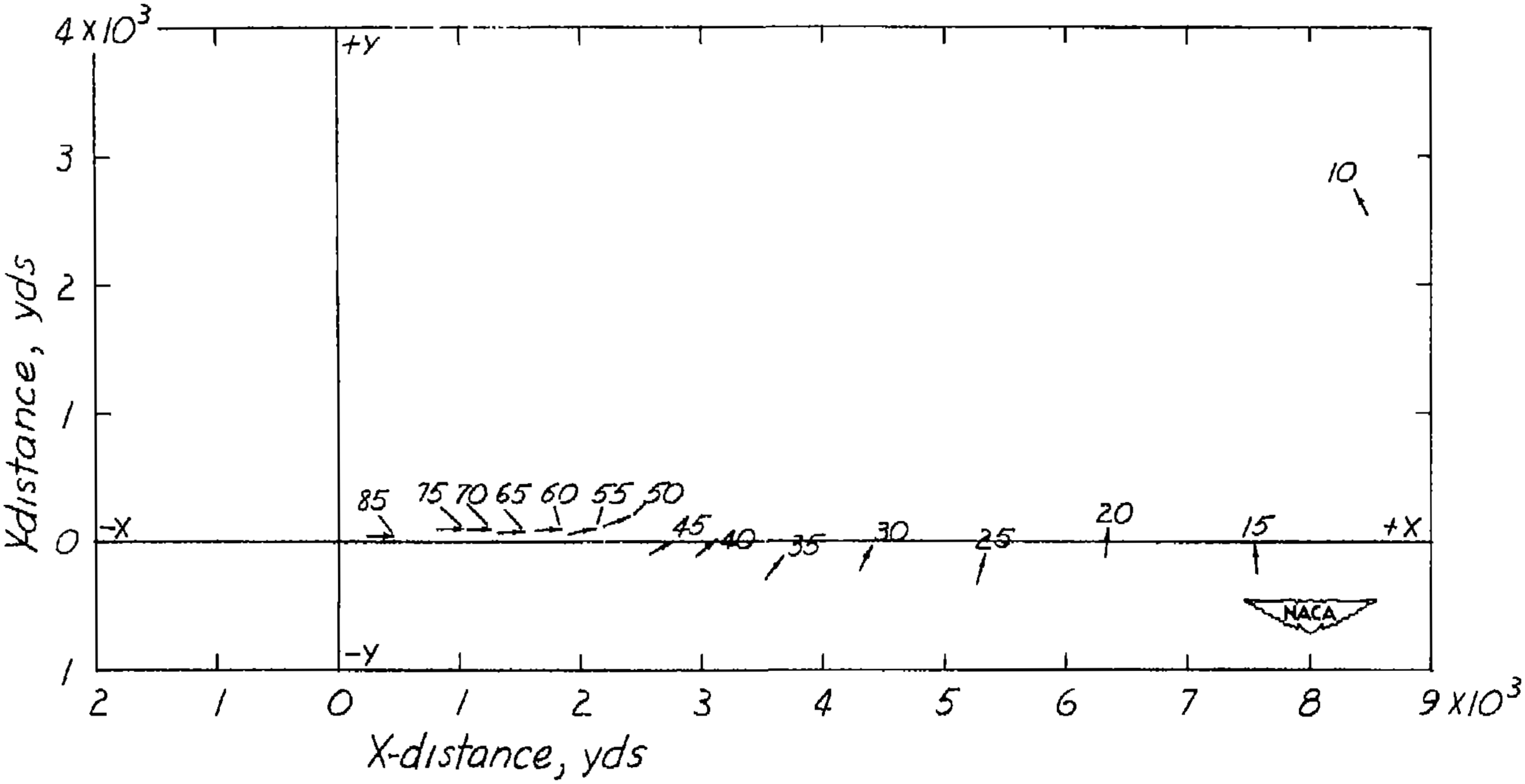
[redacted]



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 17.- Continued.

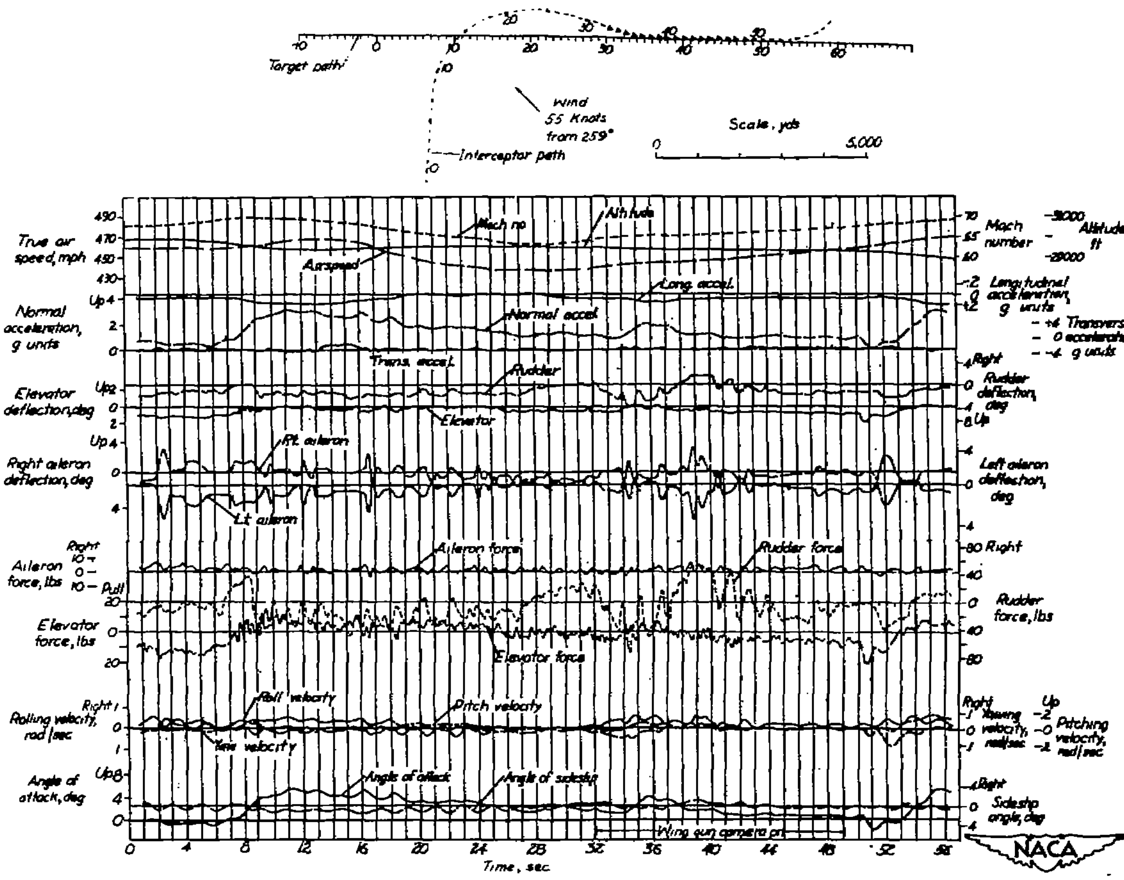
[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 17.- Concluded.

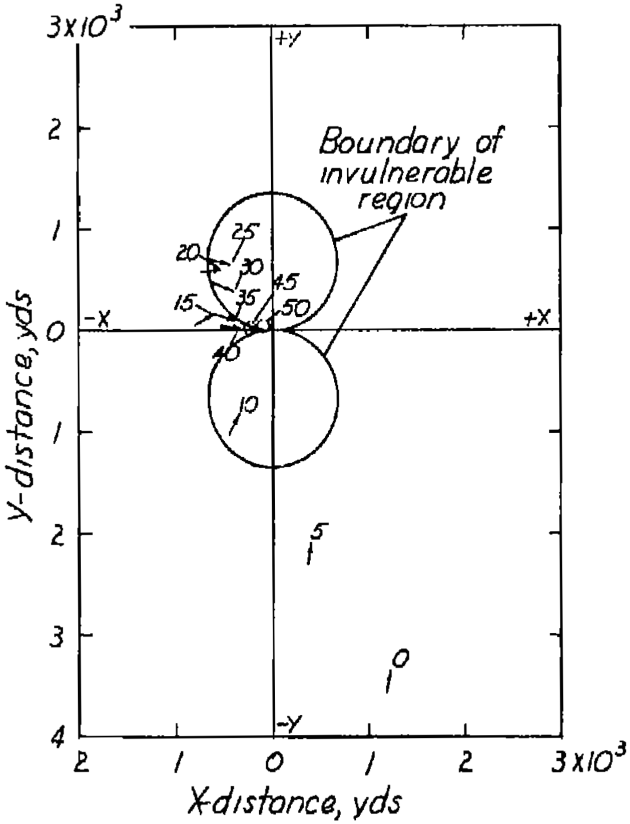
[redacted]



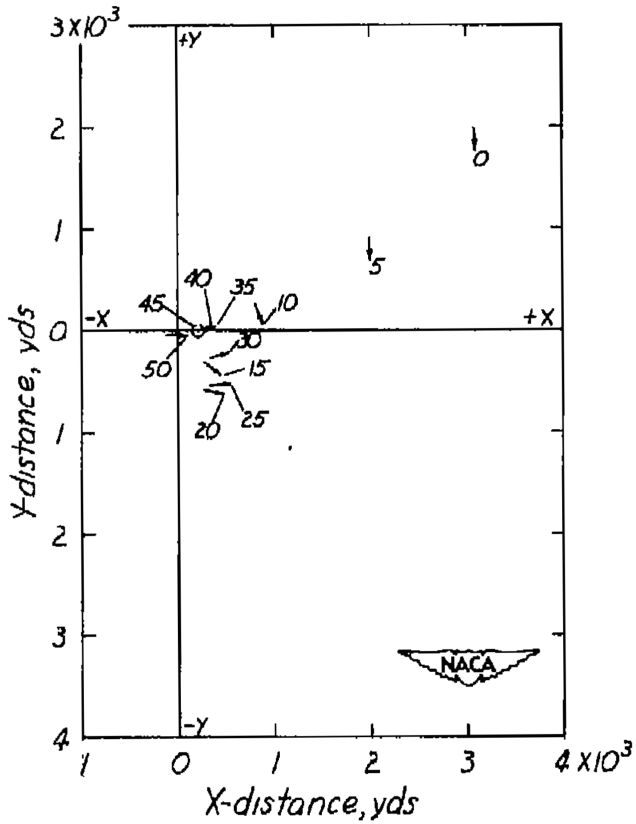
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 18.- Interceptor airplane attacking target airplane from a perpendicular encounter.

[redacted]



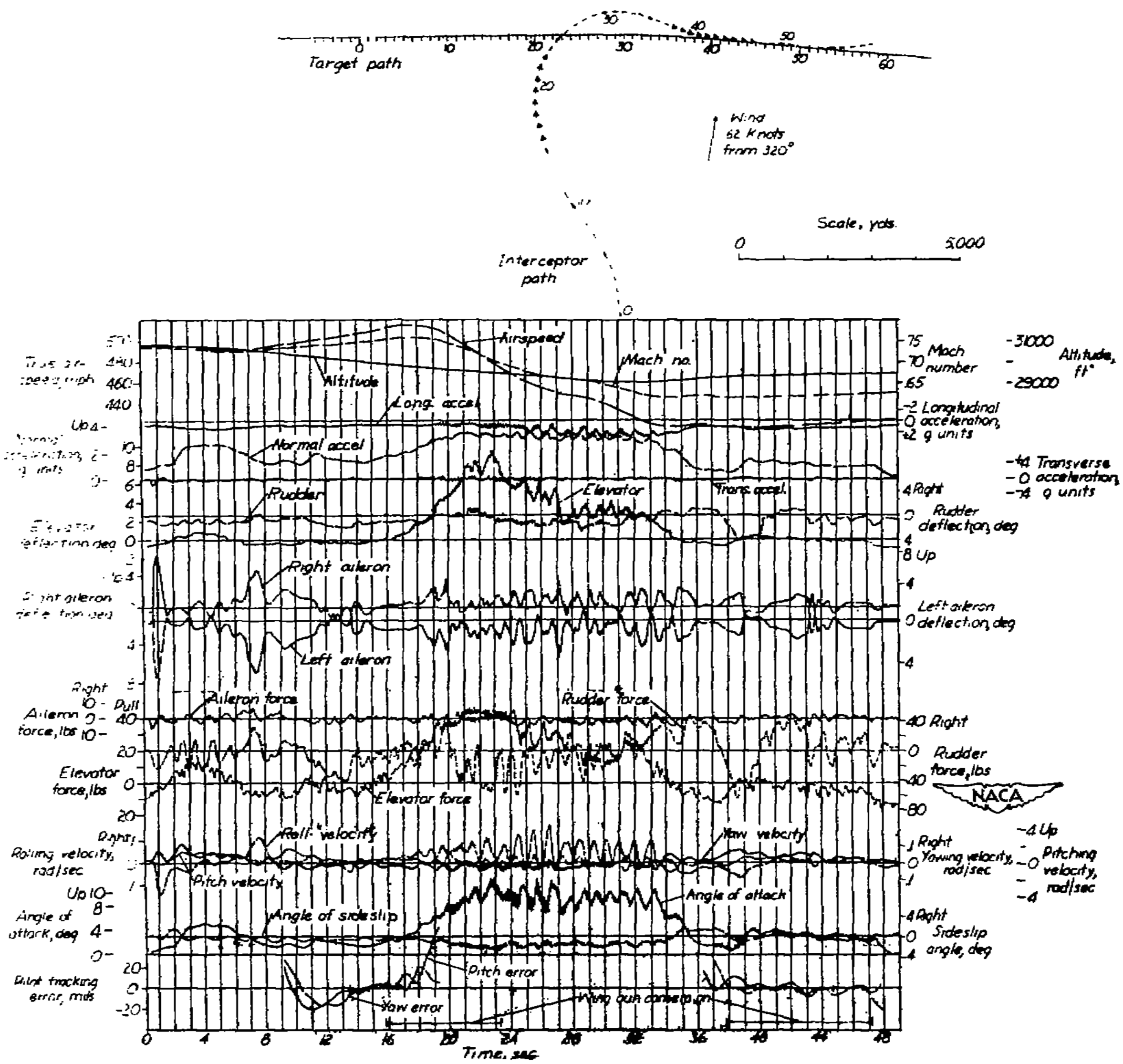
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

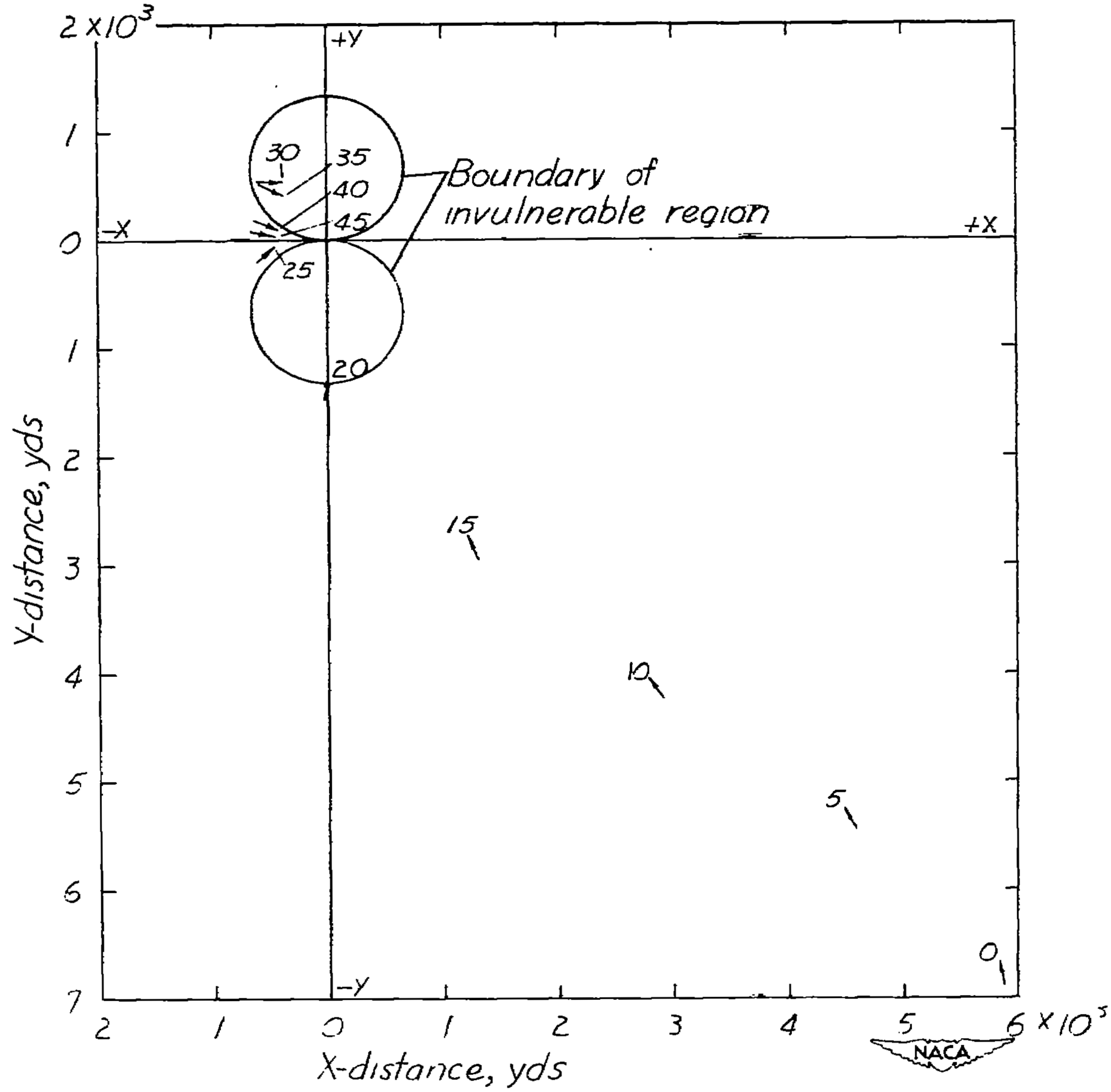
Figure 18.- Concluded.

[redacted]



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

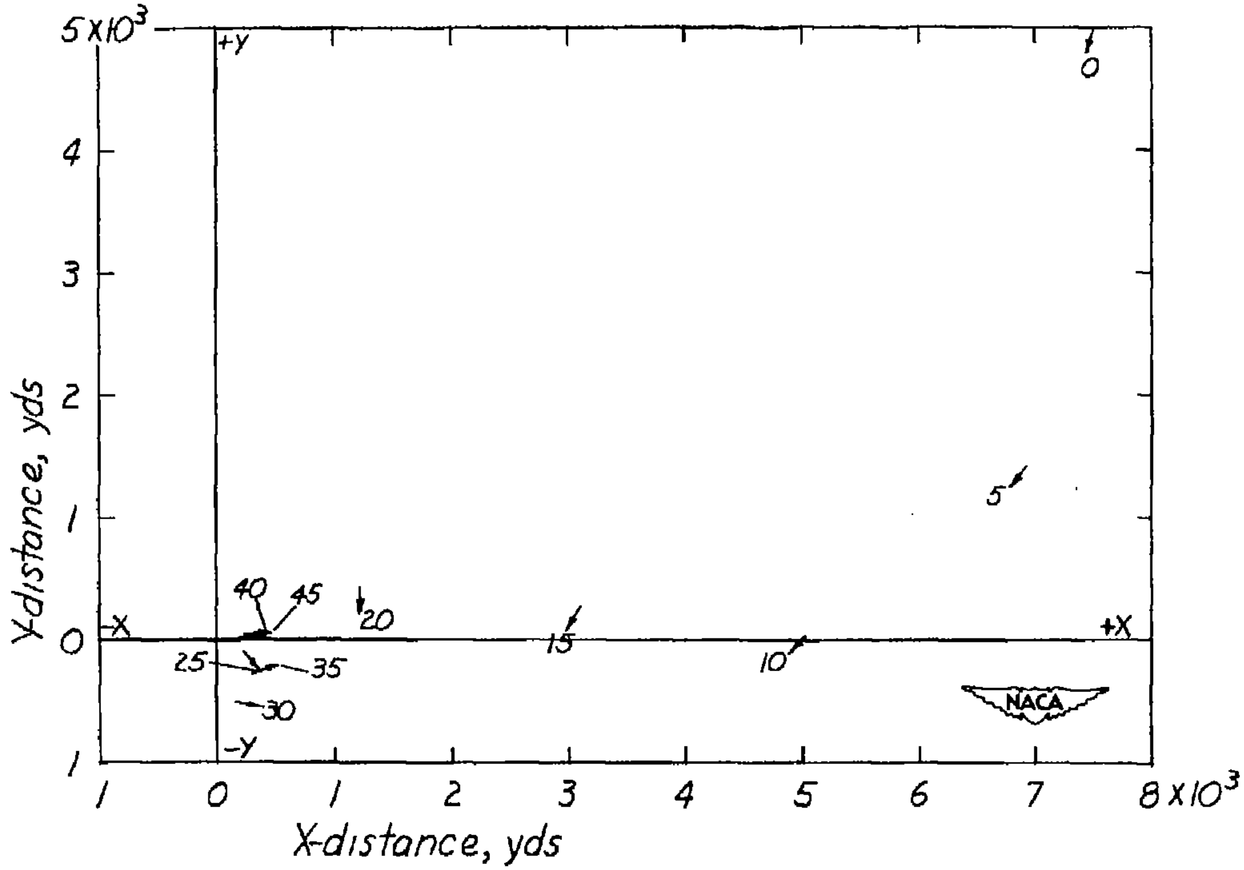
Figure 19.- Interceptor airplane attacking target airplane from a perpendicular encounter.



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 19.- Continued.

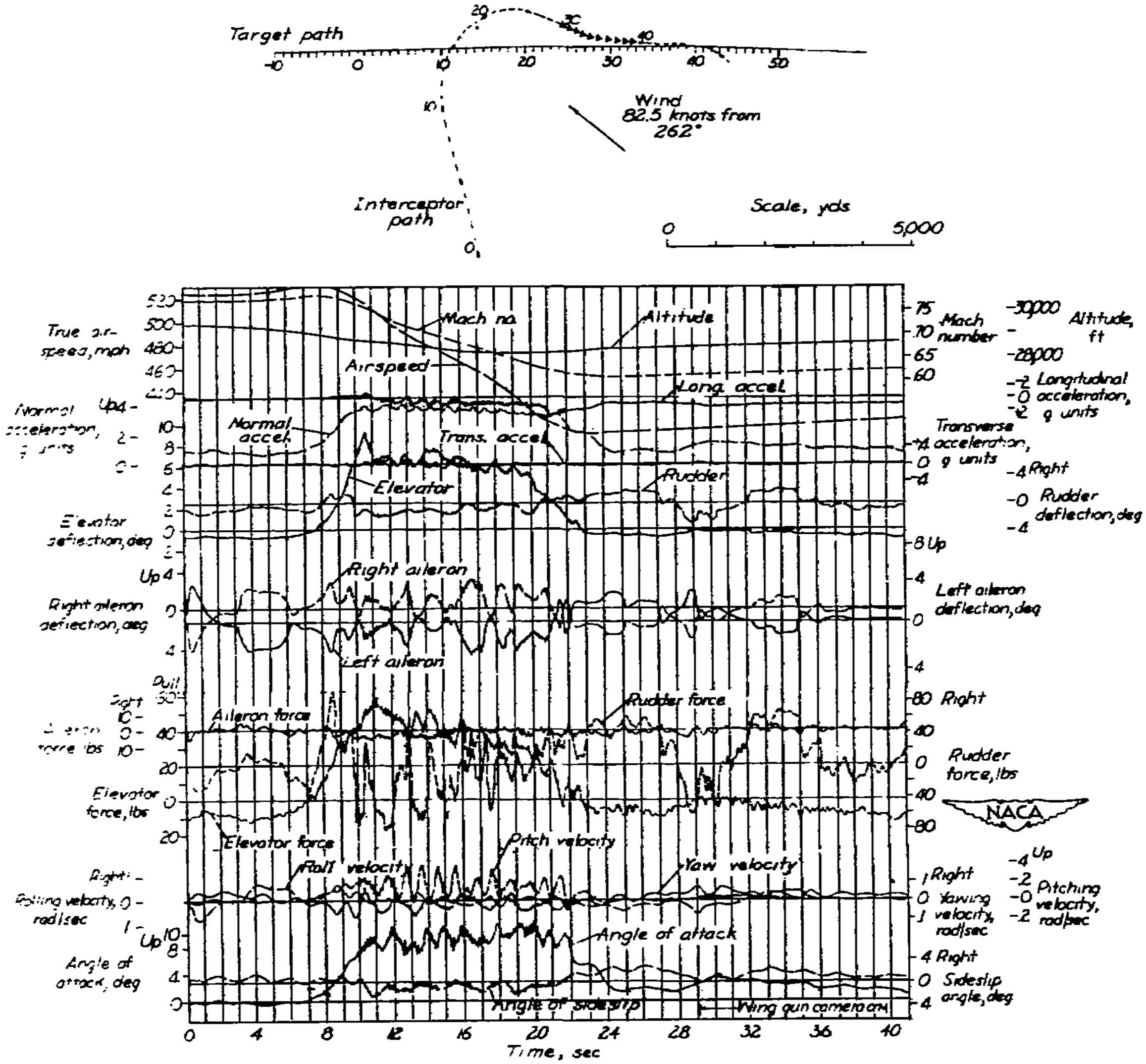
[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 19.- Concluded.

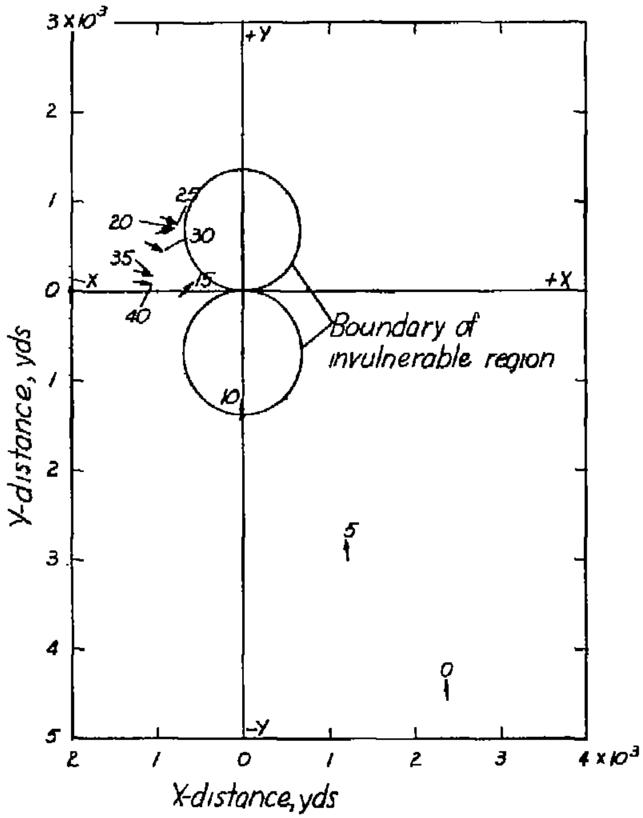
[redacted]



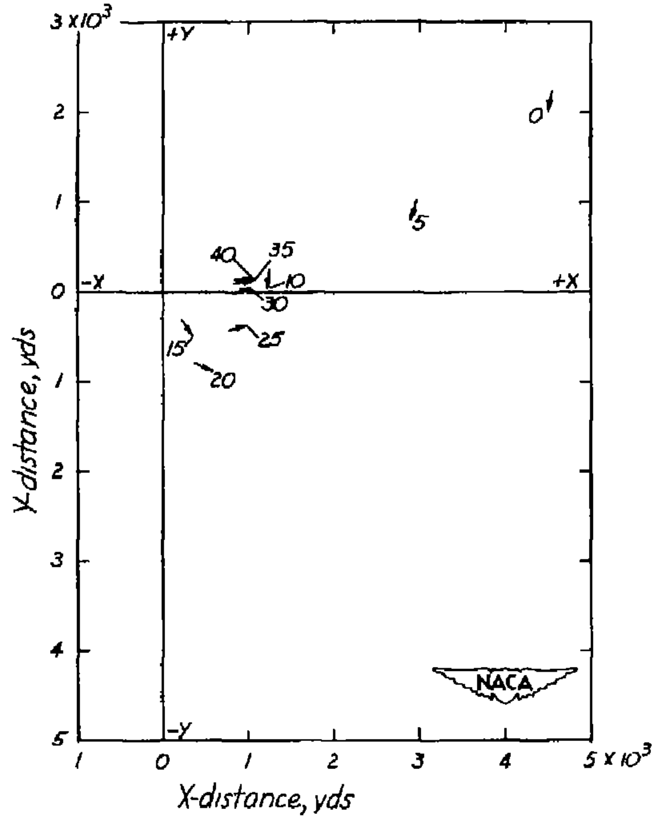
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 20.- Interceptor airplane attacking target airplane from a perpendicular encounter.

[redacted]



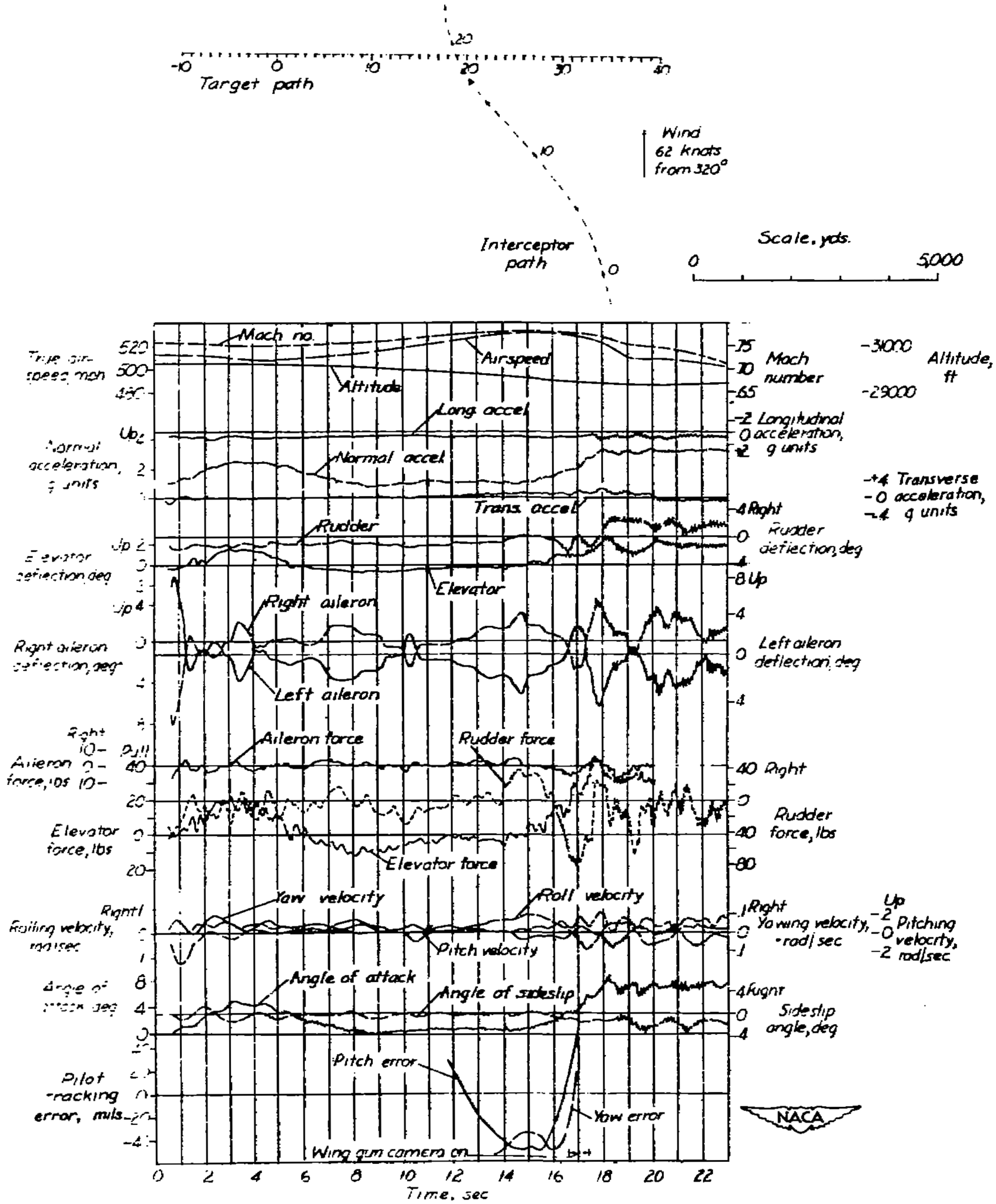
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

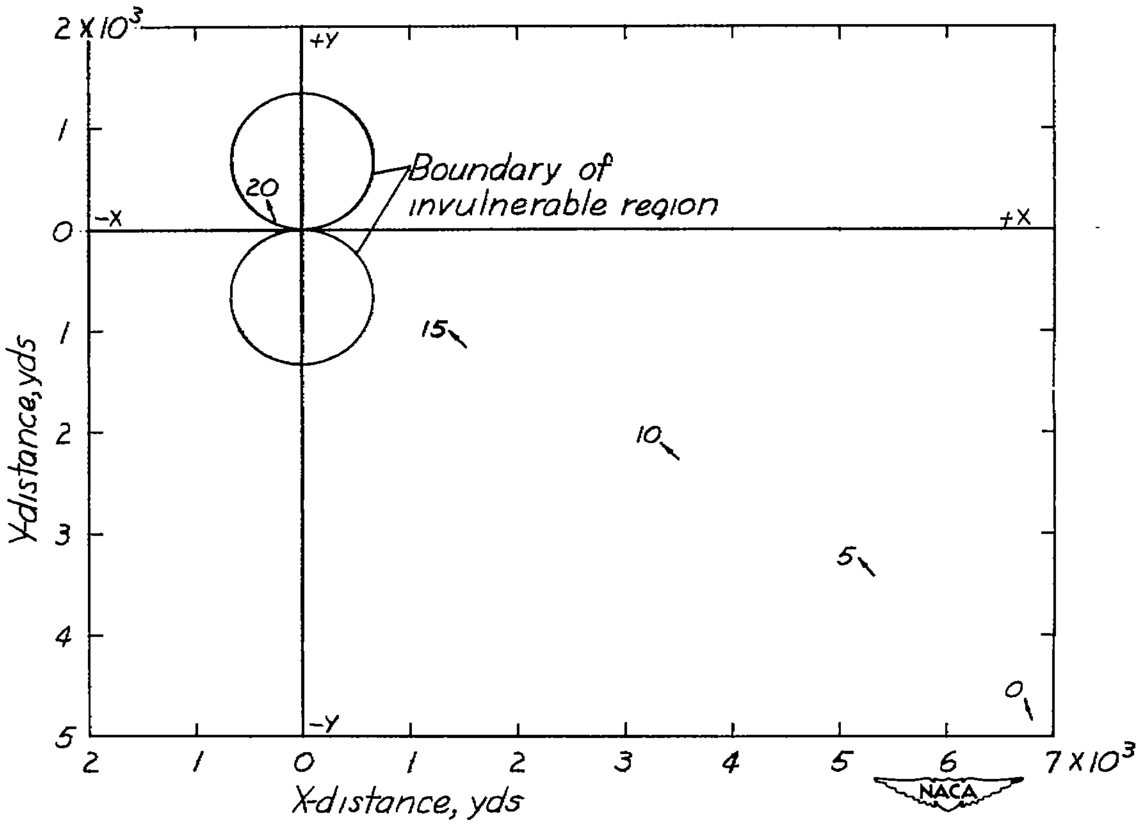
Figure 20.- Concluded.

[redacted]



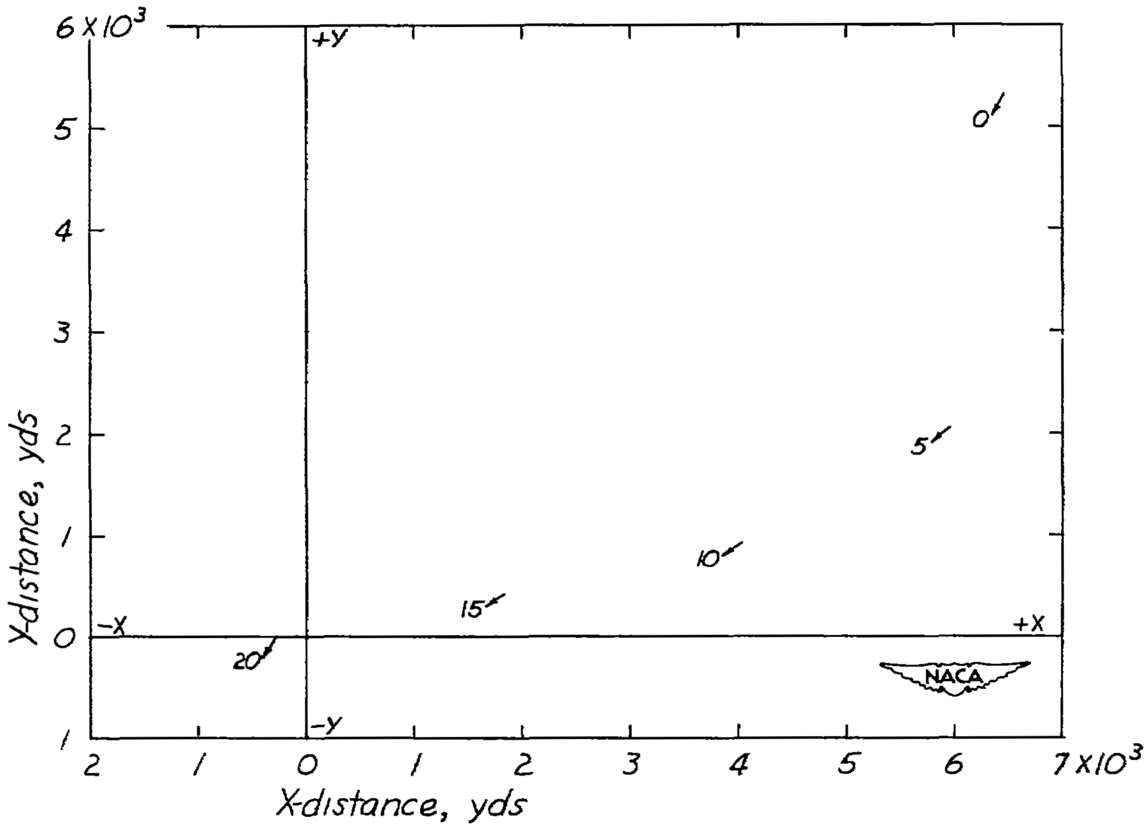
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 21.- Interceptor airplane attacking target airplane from a perpendicular encounter.



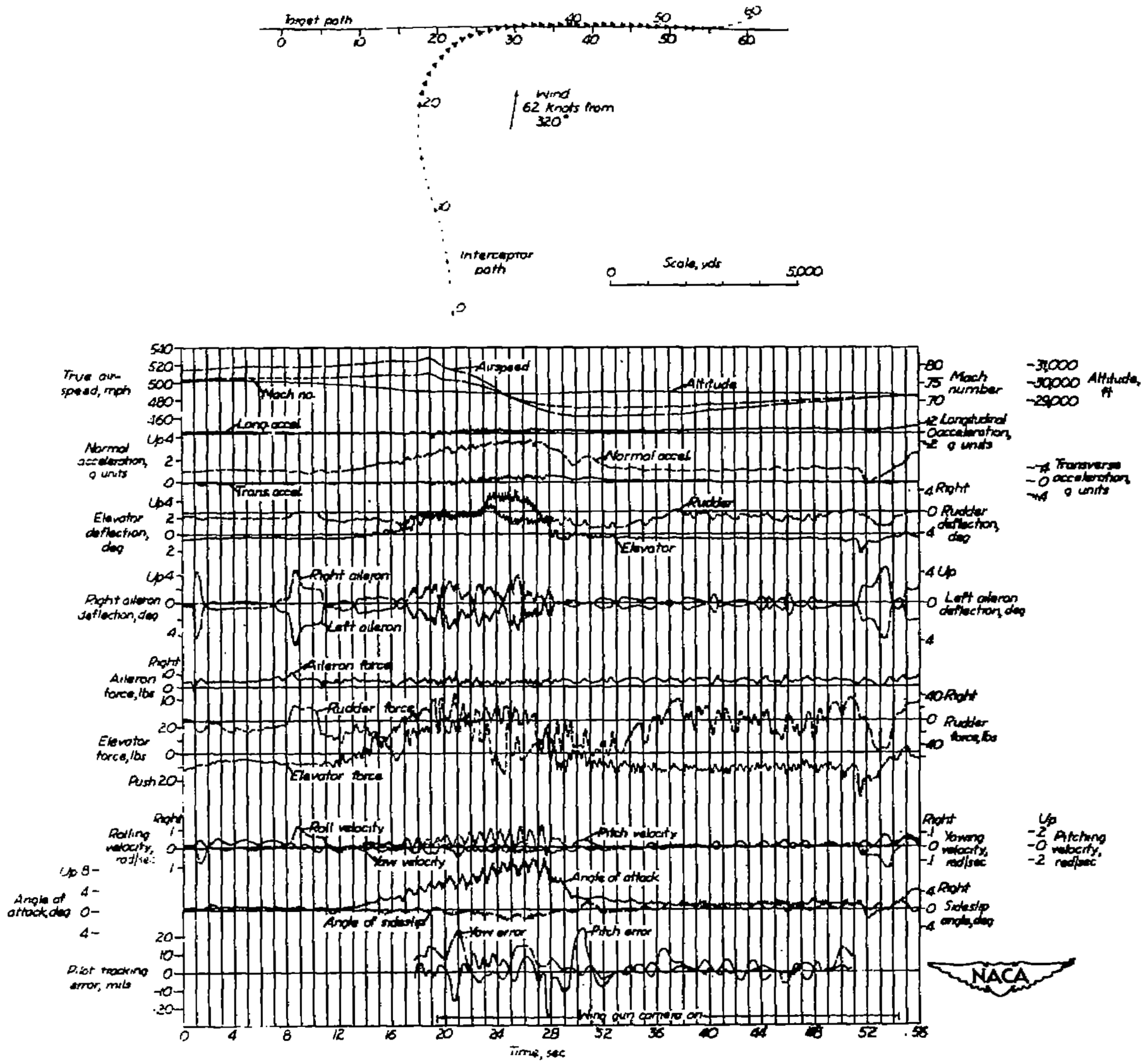
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 21.- Continued.



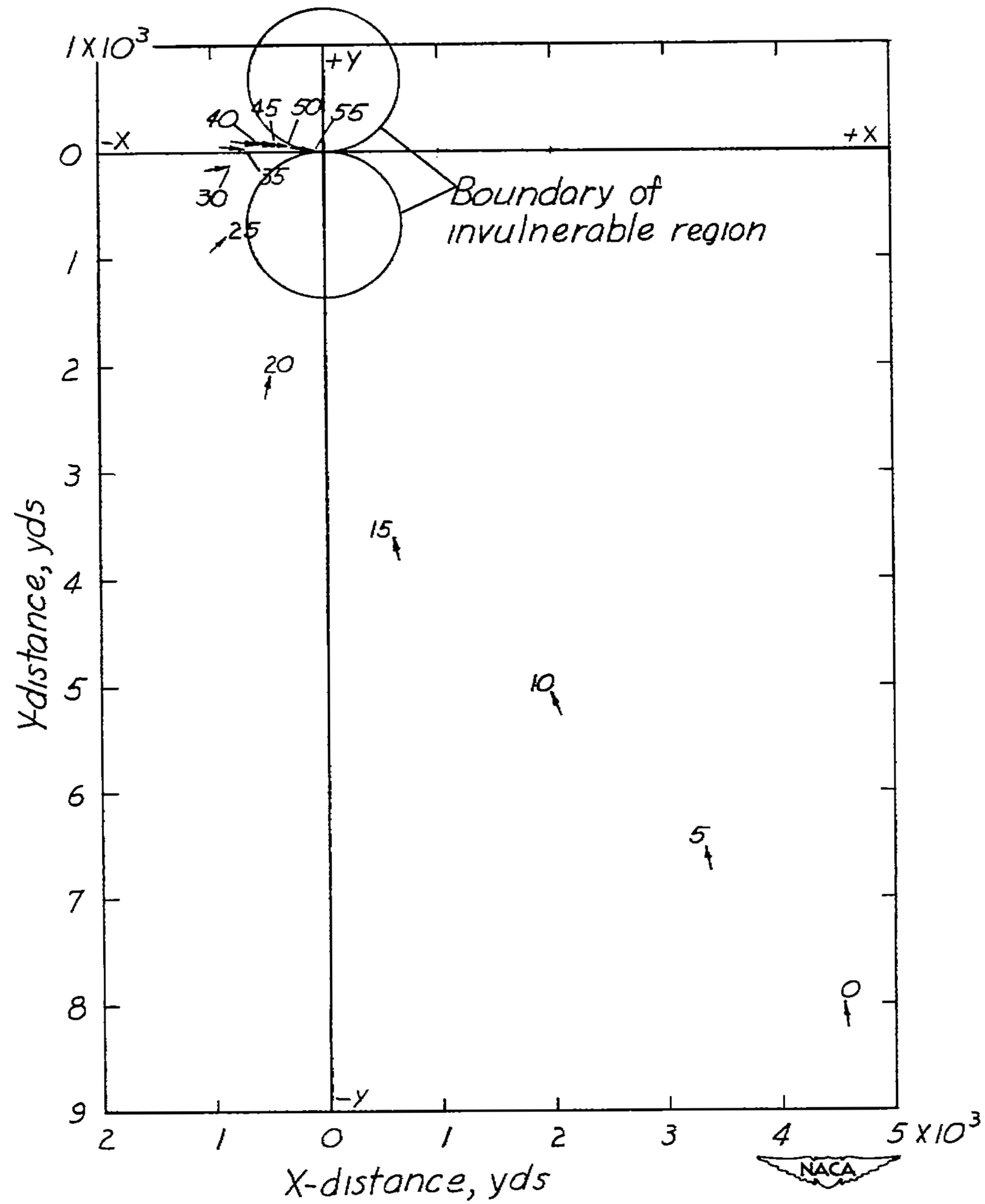
(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 21.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

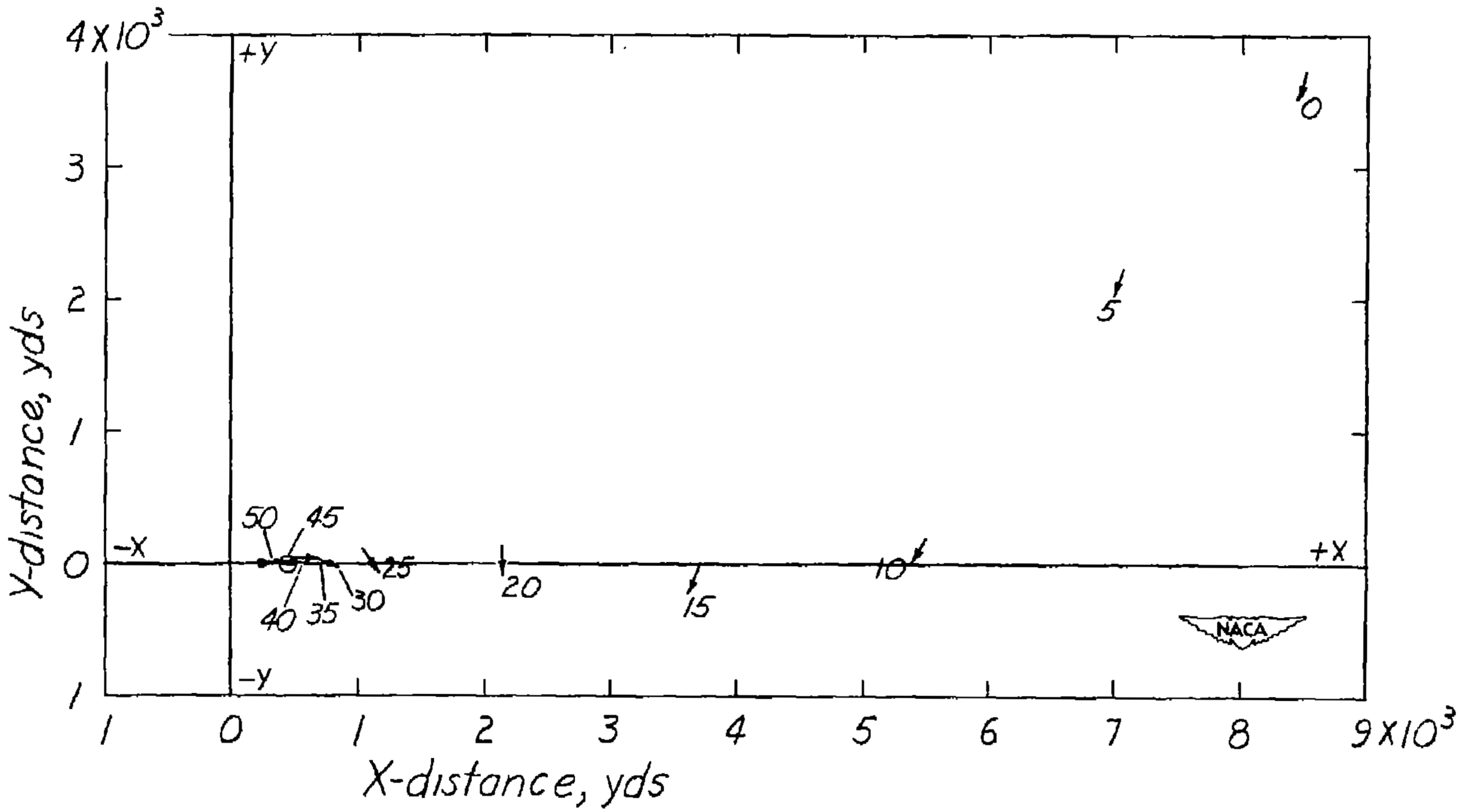
Figure 22.- Interceptor airplane attacking target airplane from a perpendicular encounter.



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 22.- Continued.

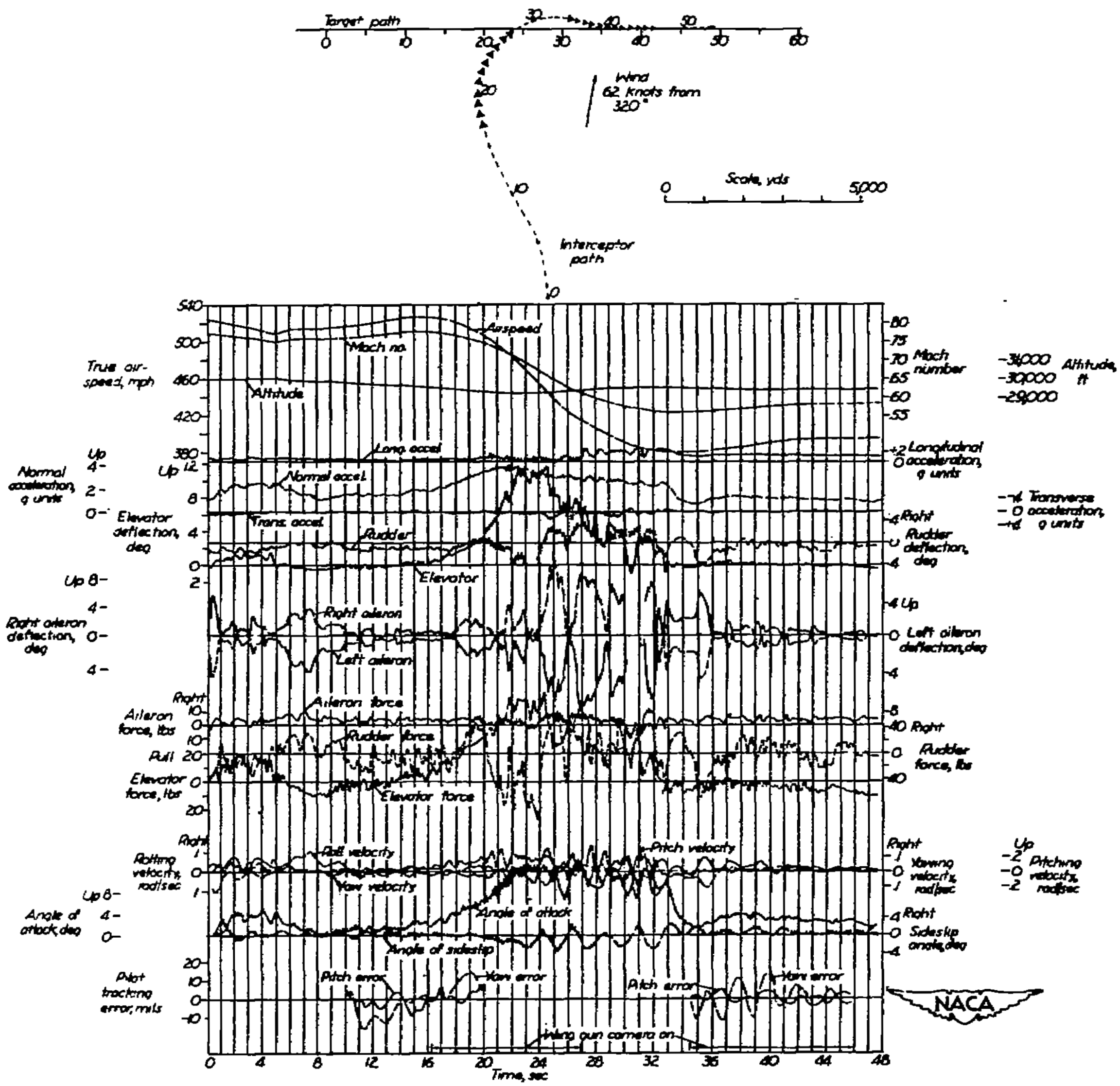
[redacted]



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

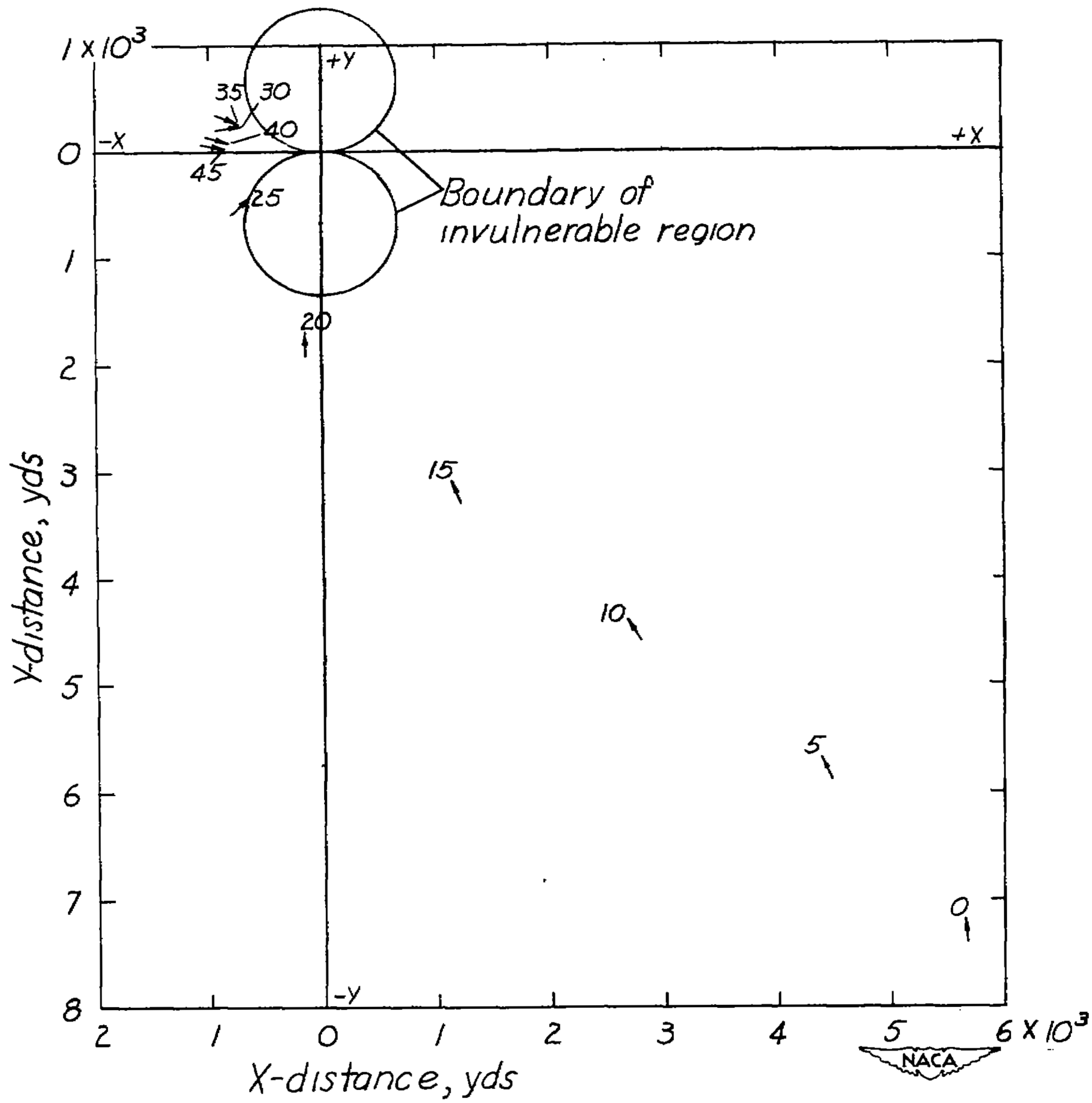
Figure 22.- Concluded.

[redacted]



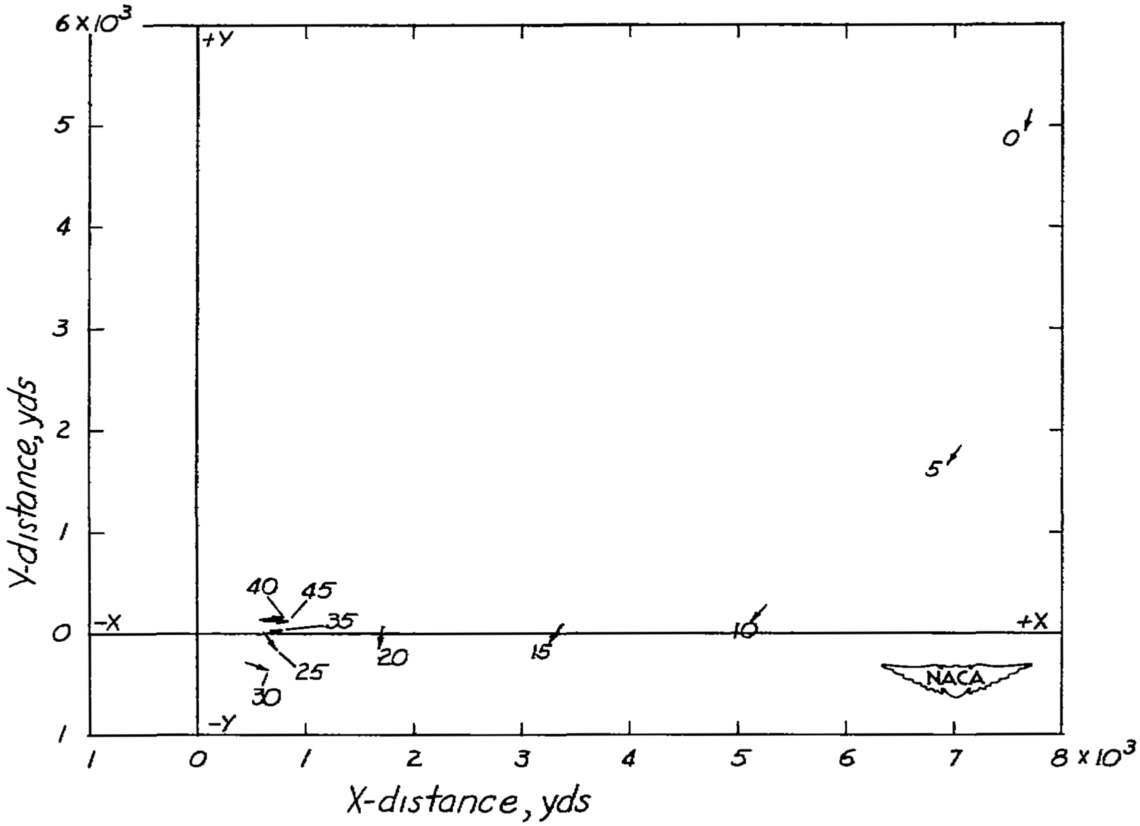
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 23.- Interceptor airplane attacking target airplane from a perpendicular encounter.



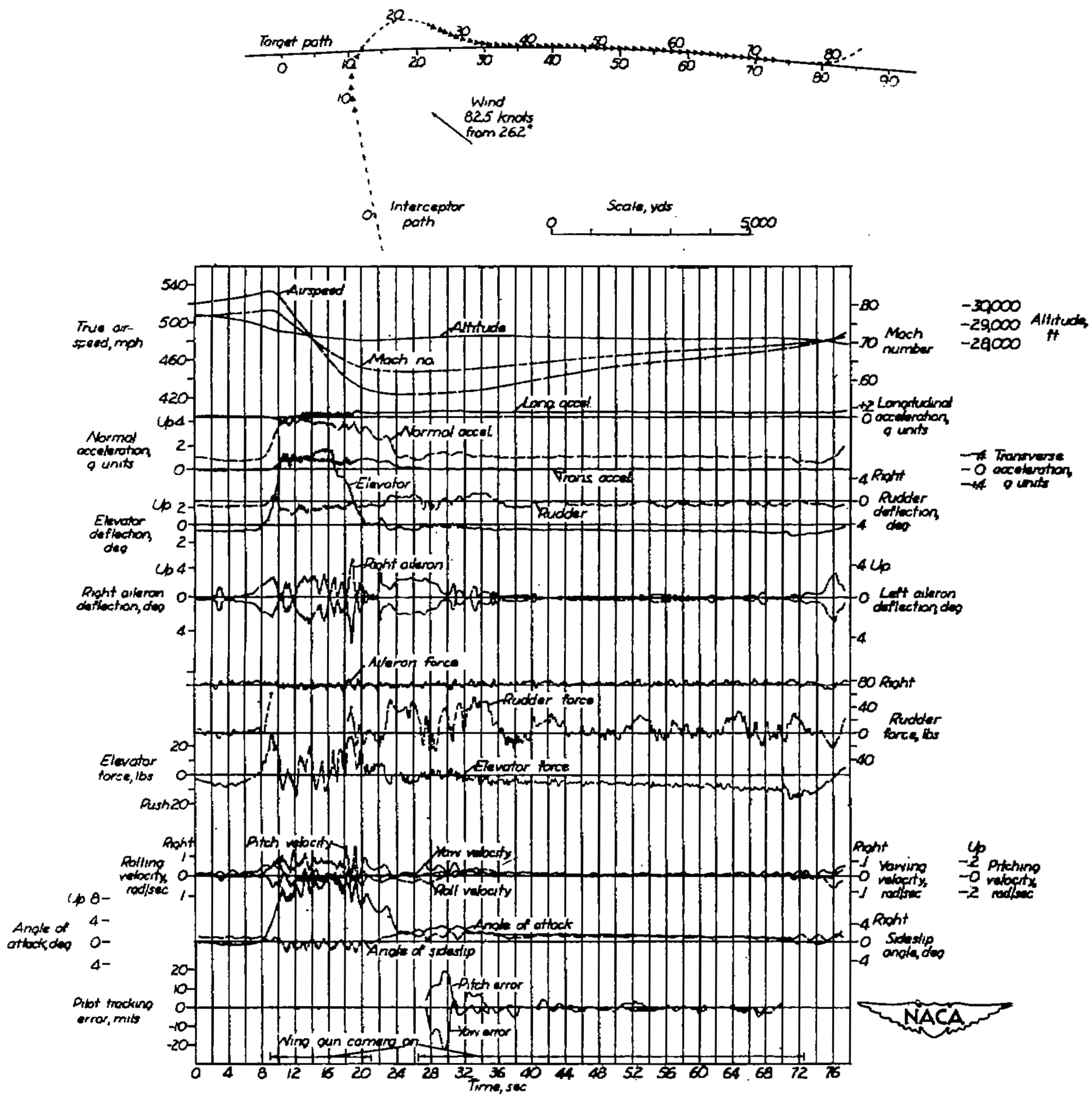
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 23.- Continued.



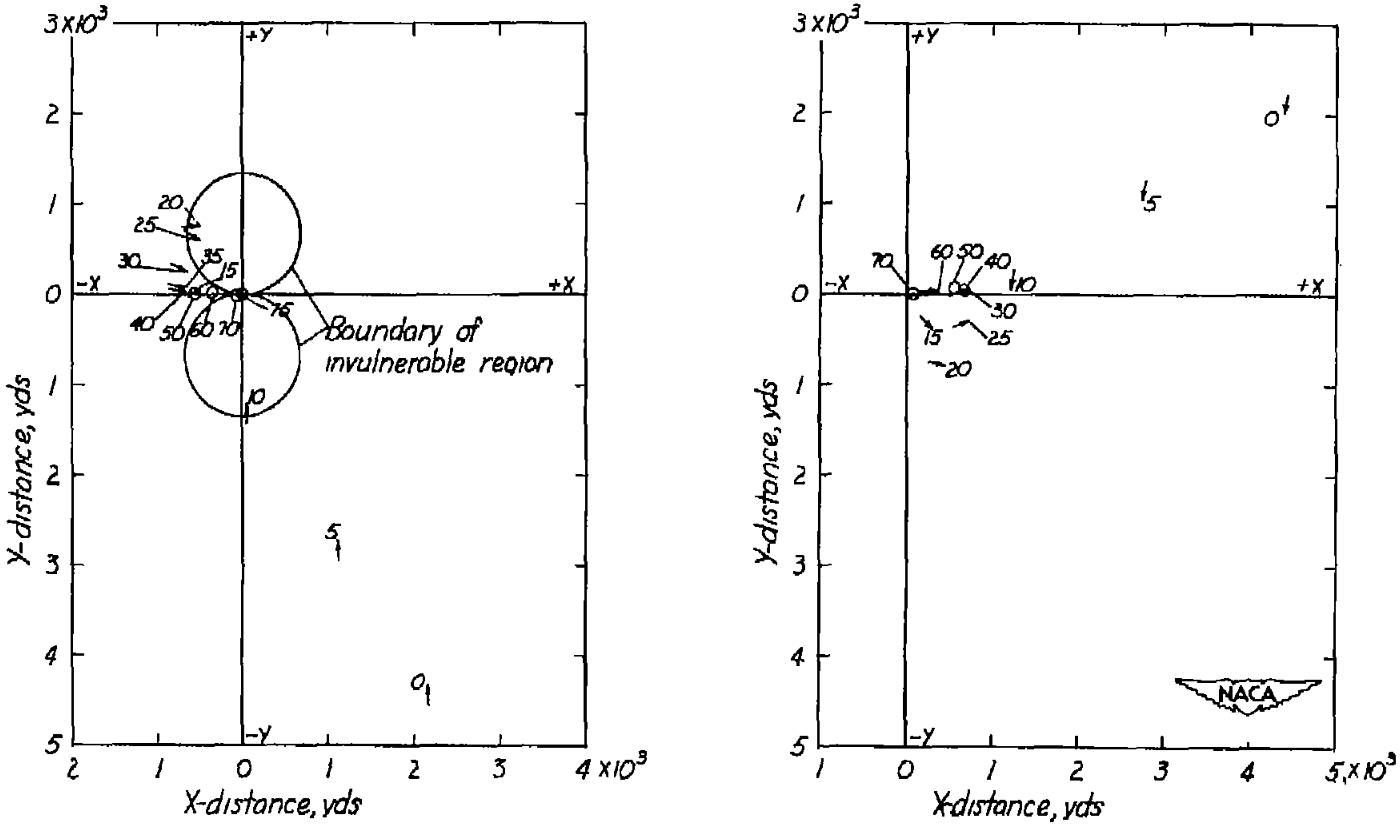
(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 23.- Concluded.



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

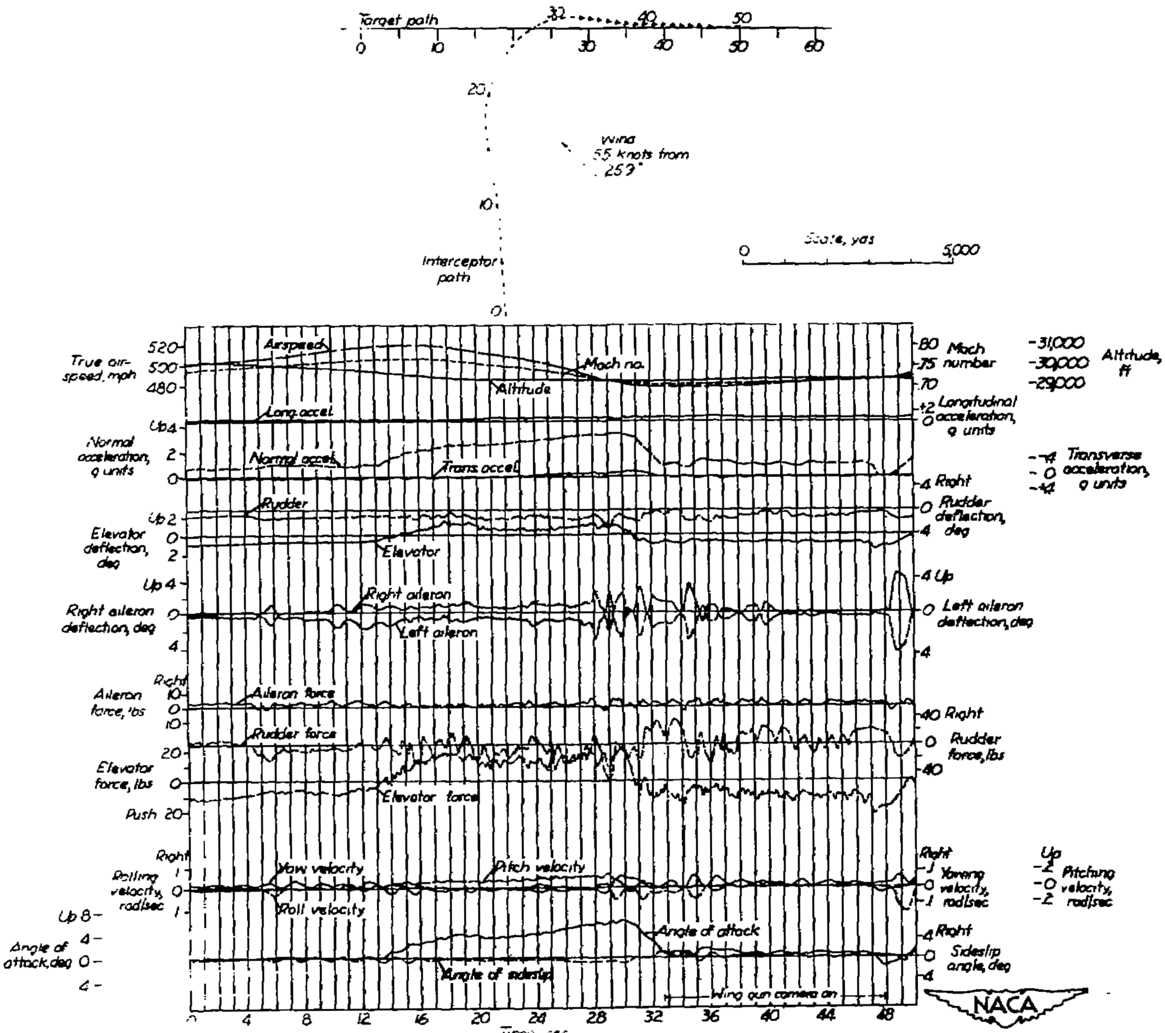
Figure 24.- Interceptor airplane attacking target airplane from a perpendicular encounter.



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

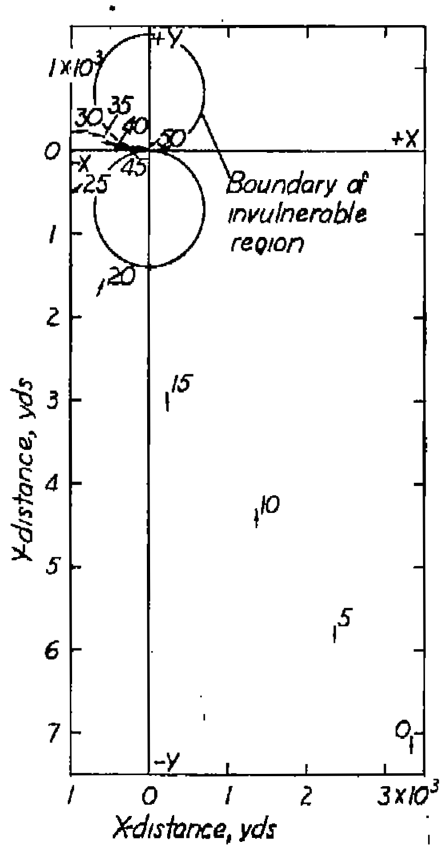
Figure 24.- Concluded.



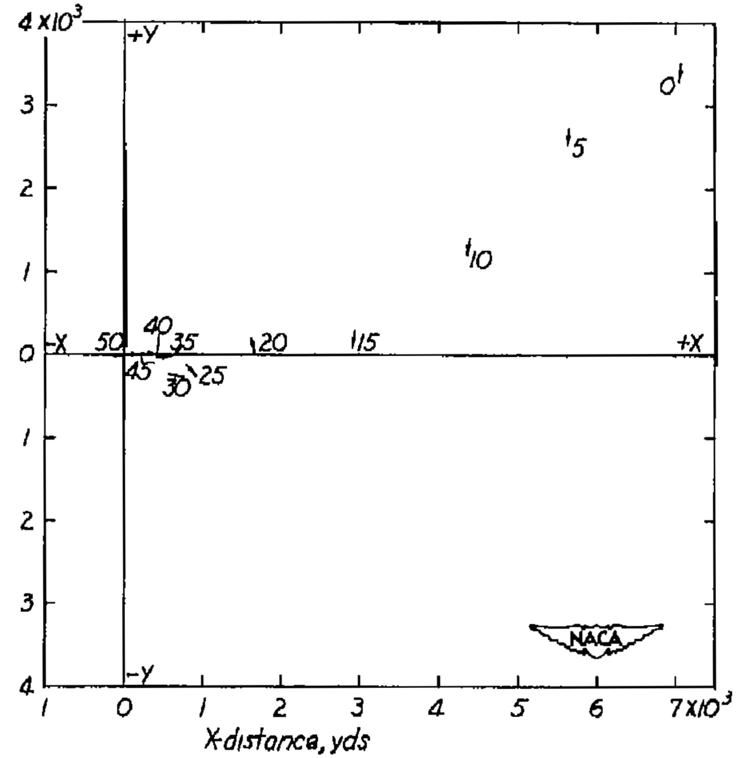
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 25.- Interceptor airplane attacking target airplane from a perpendicular encounter.

[redacted]



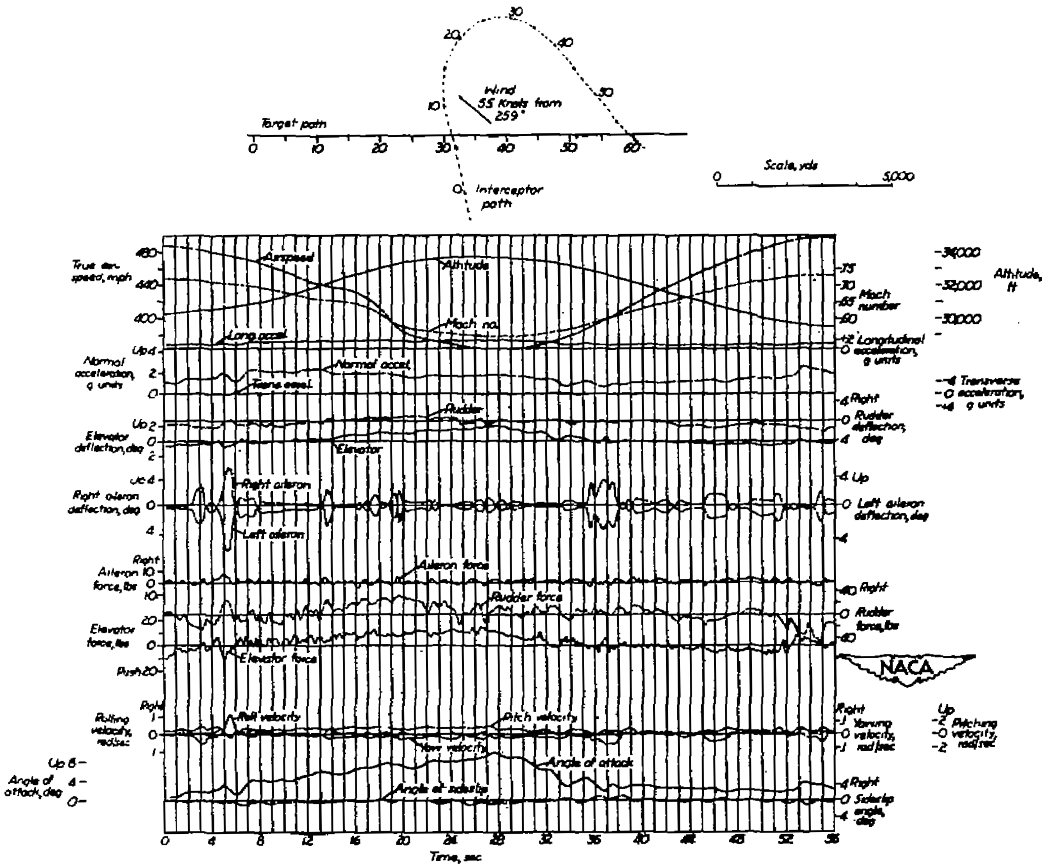
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 25.- Concluded.

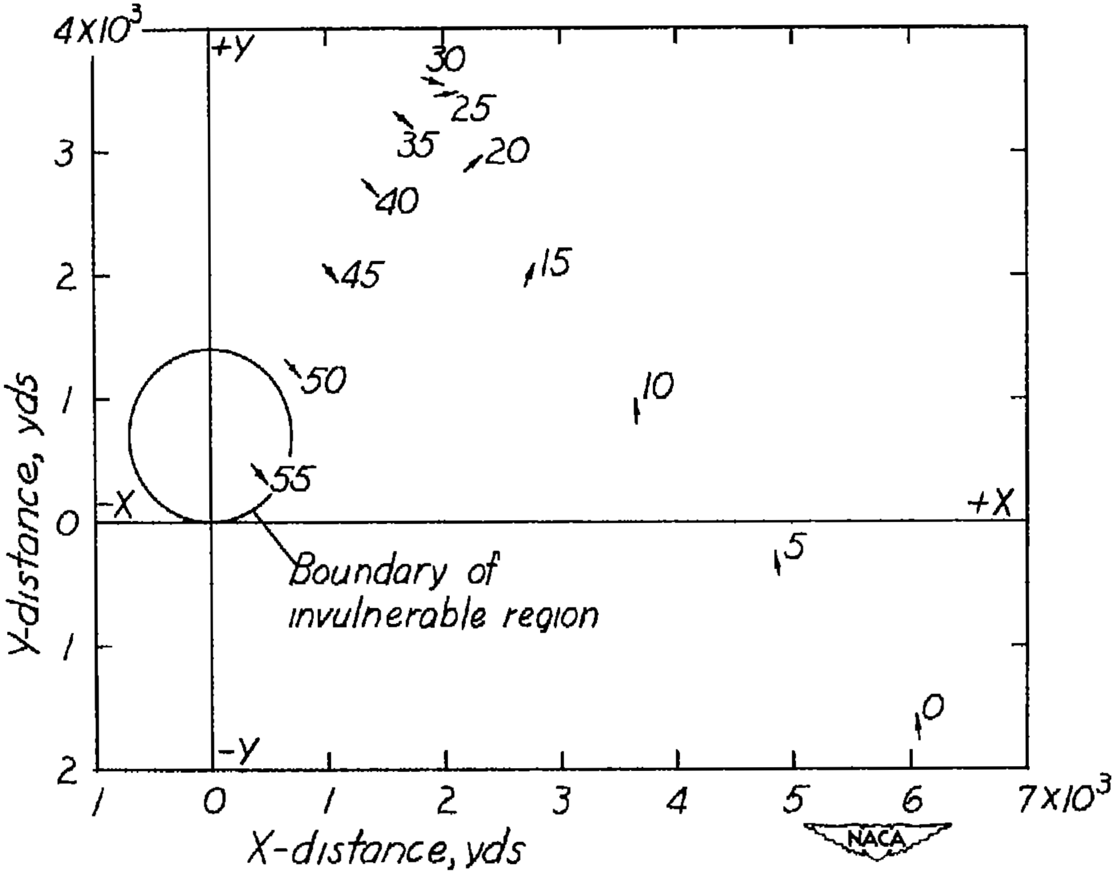
[redacted]



(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

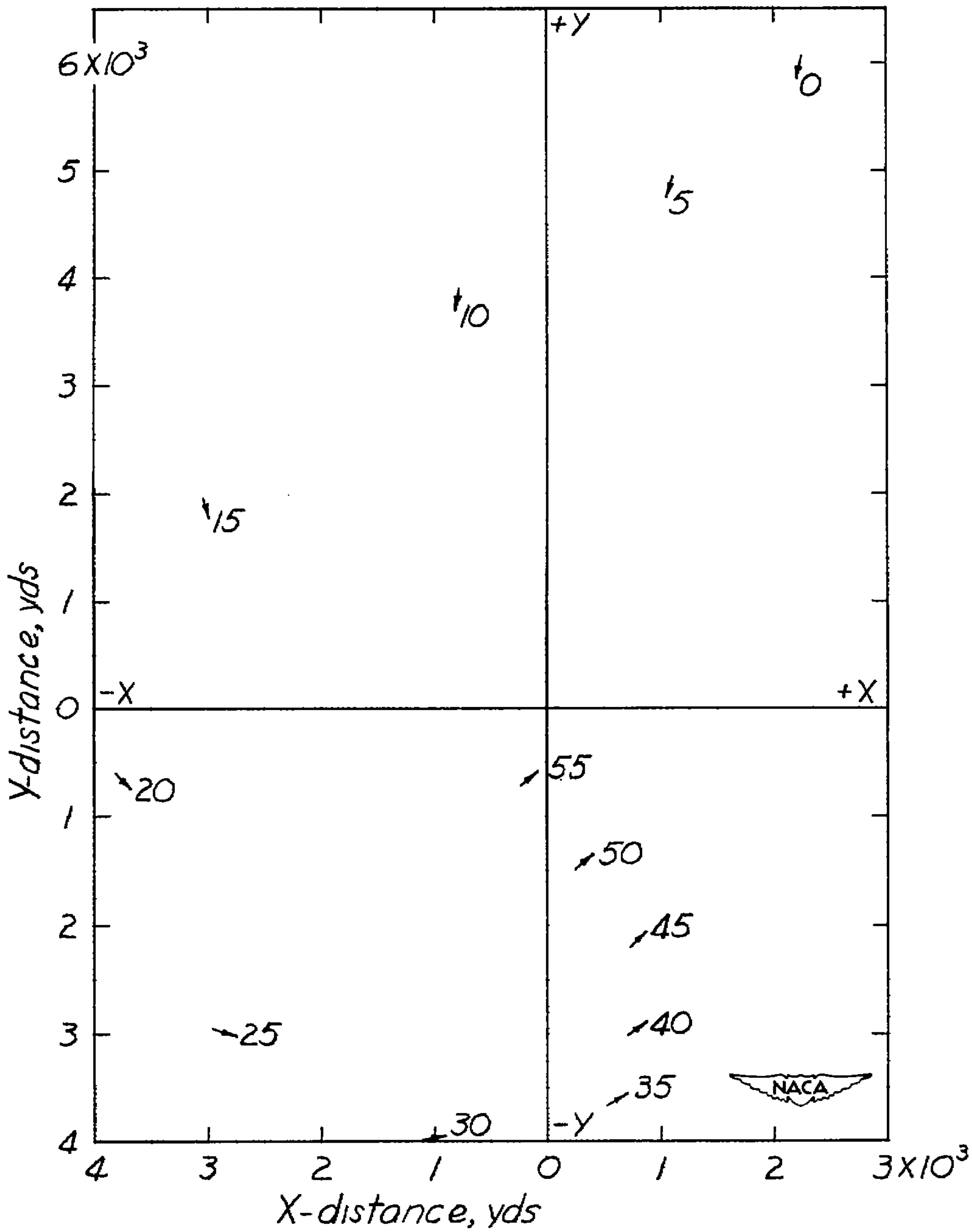
Figure 26.- Interceptor airplane attacking target airplane from a perpendicular encounter.

[redacted]



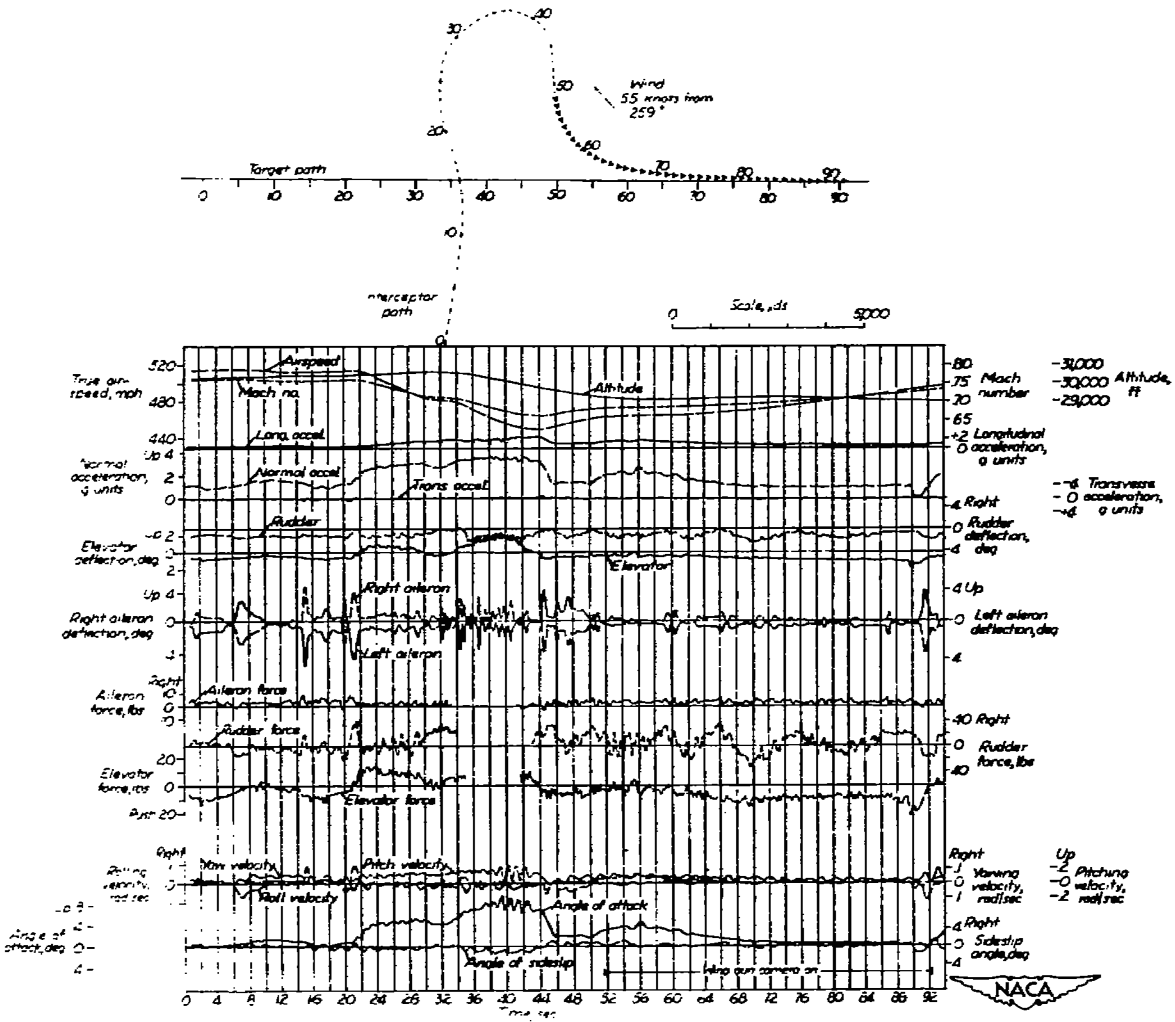
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 26.- Continued.



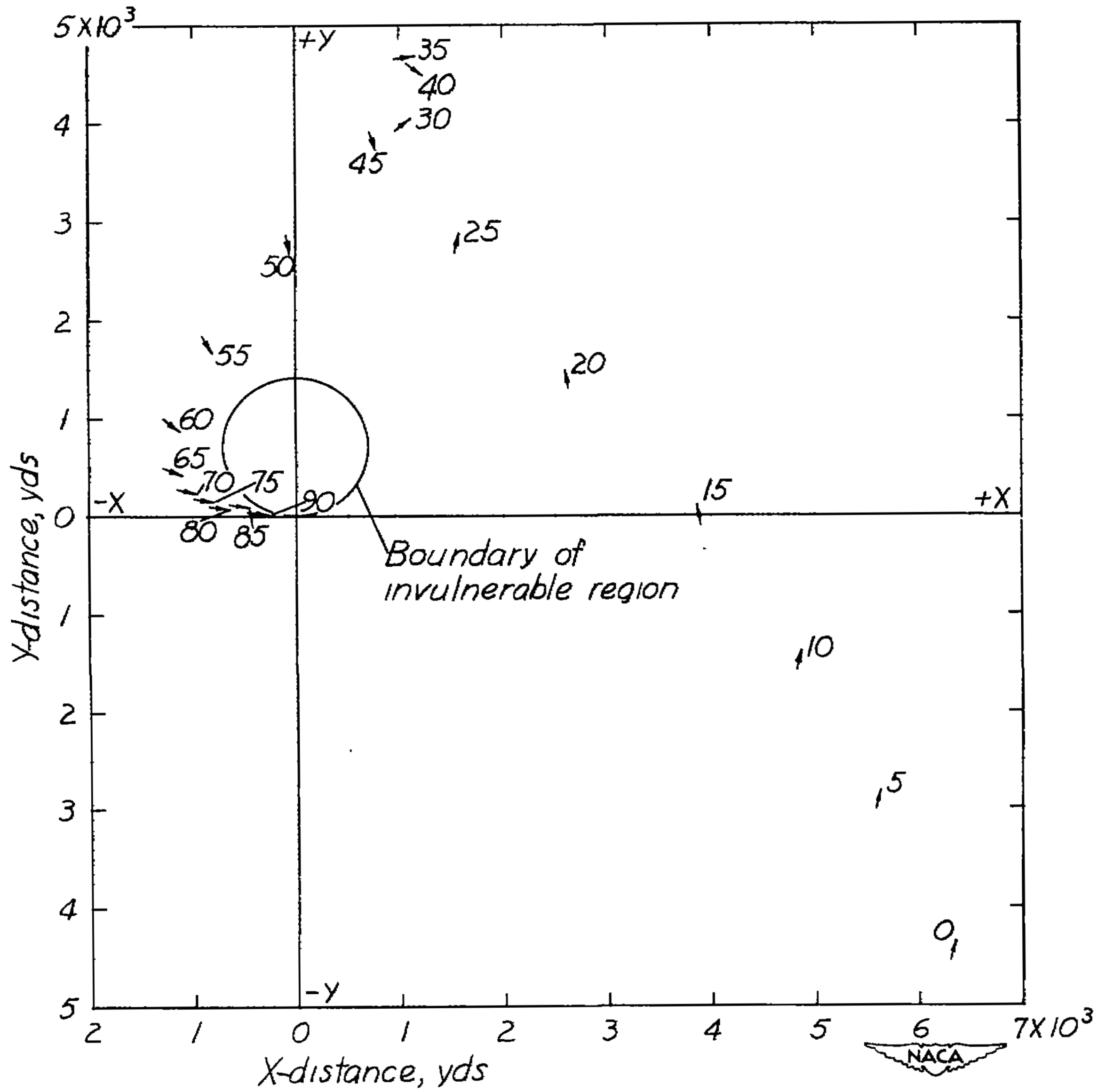
(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 26.- Concluded.



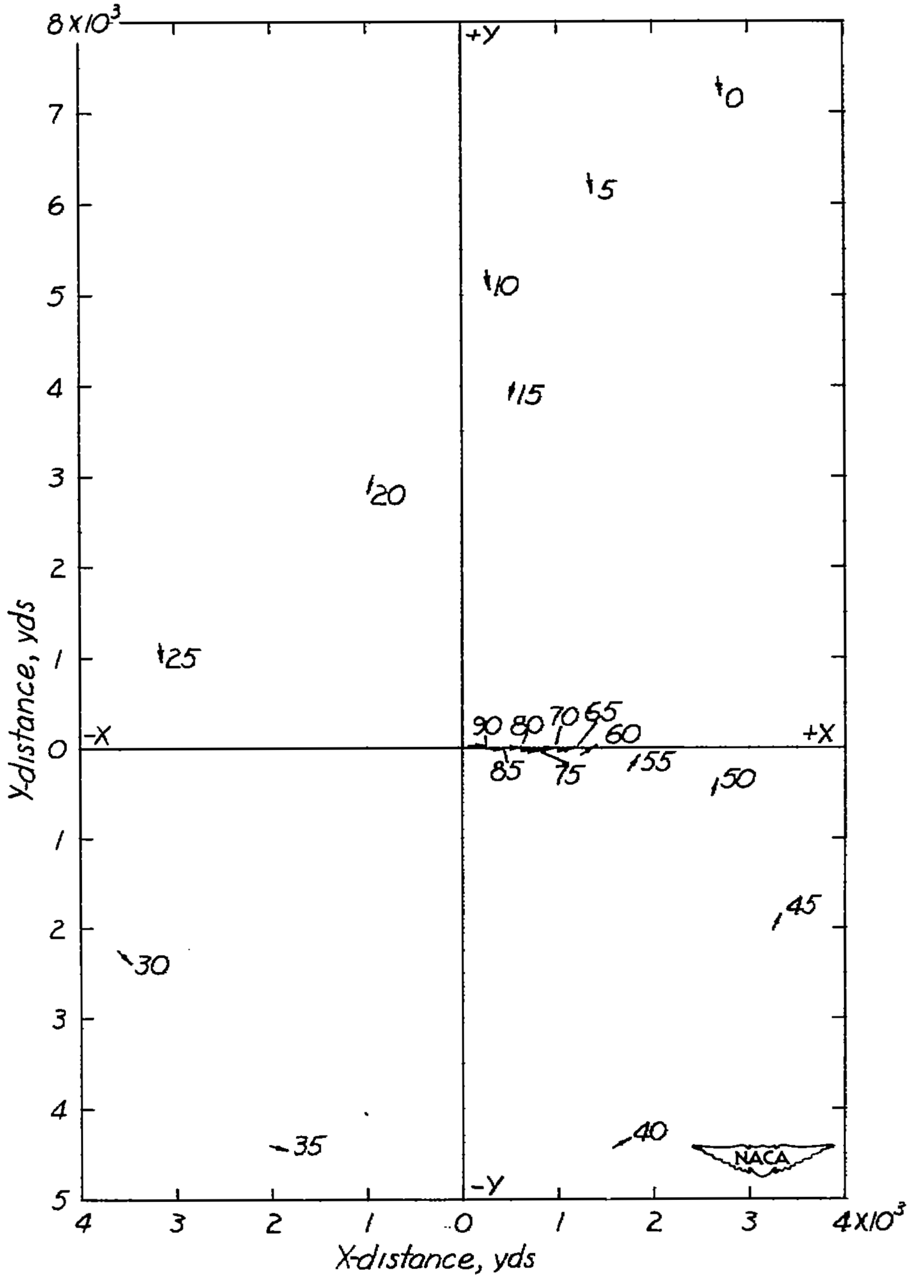
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 27.- Interceptor airplane attacking target airplane from a perpendicular encounter.



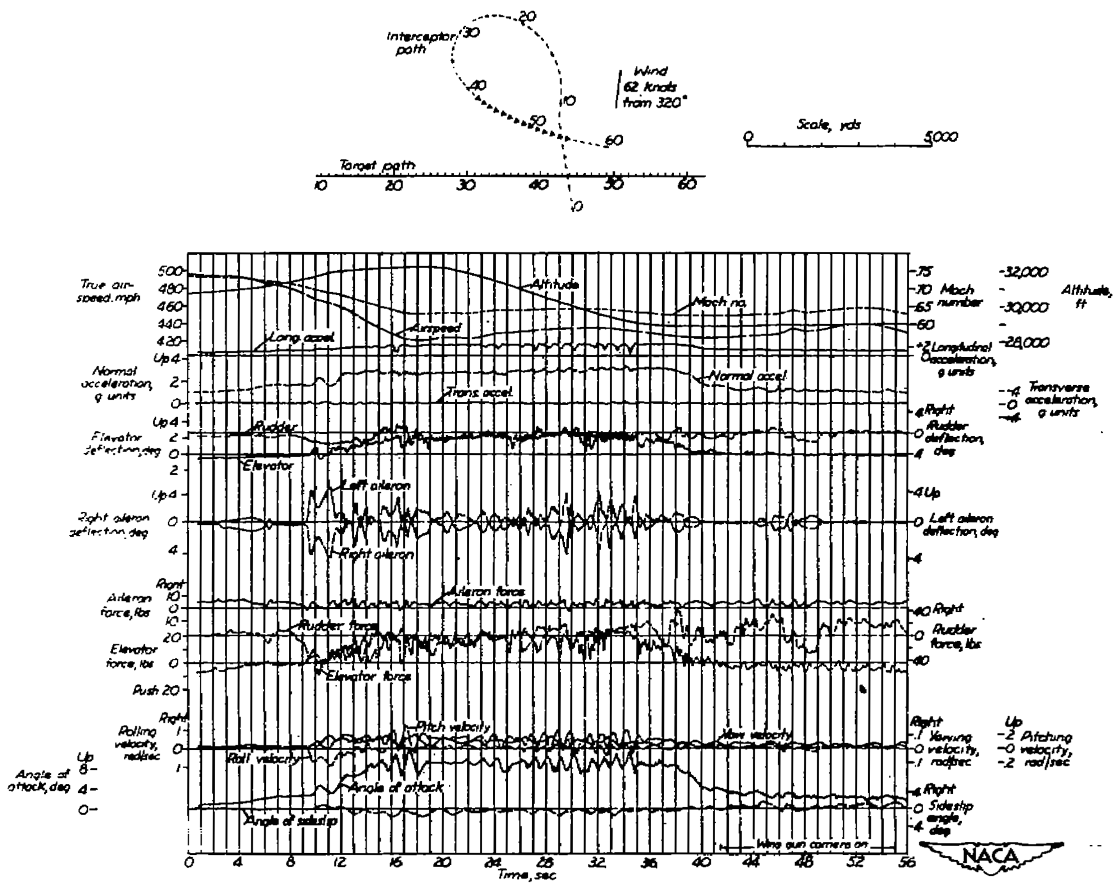
(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 27.- Continued.



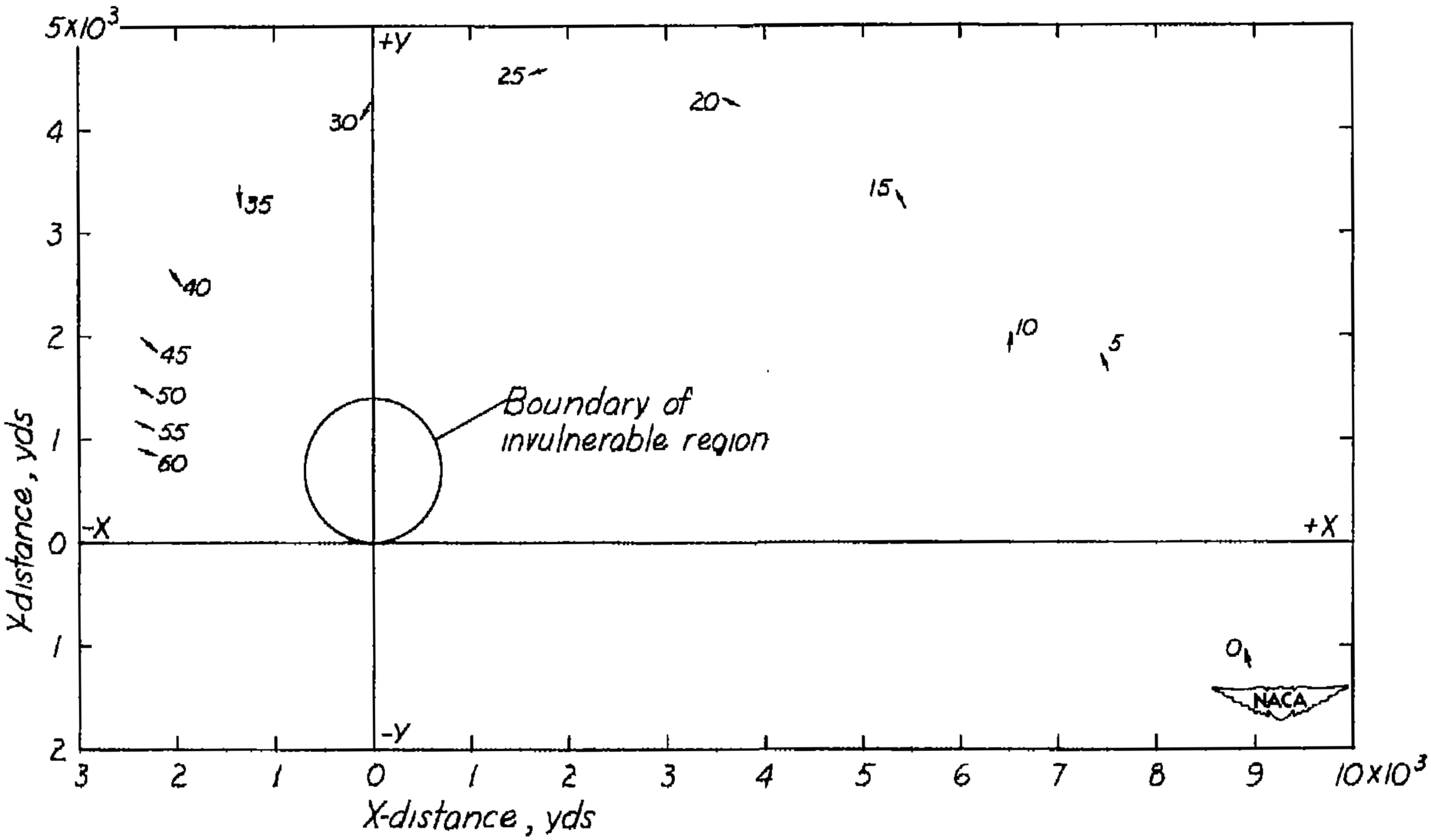
(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 27.- Concluded.



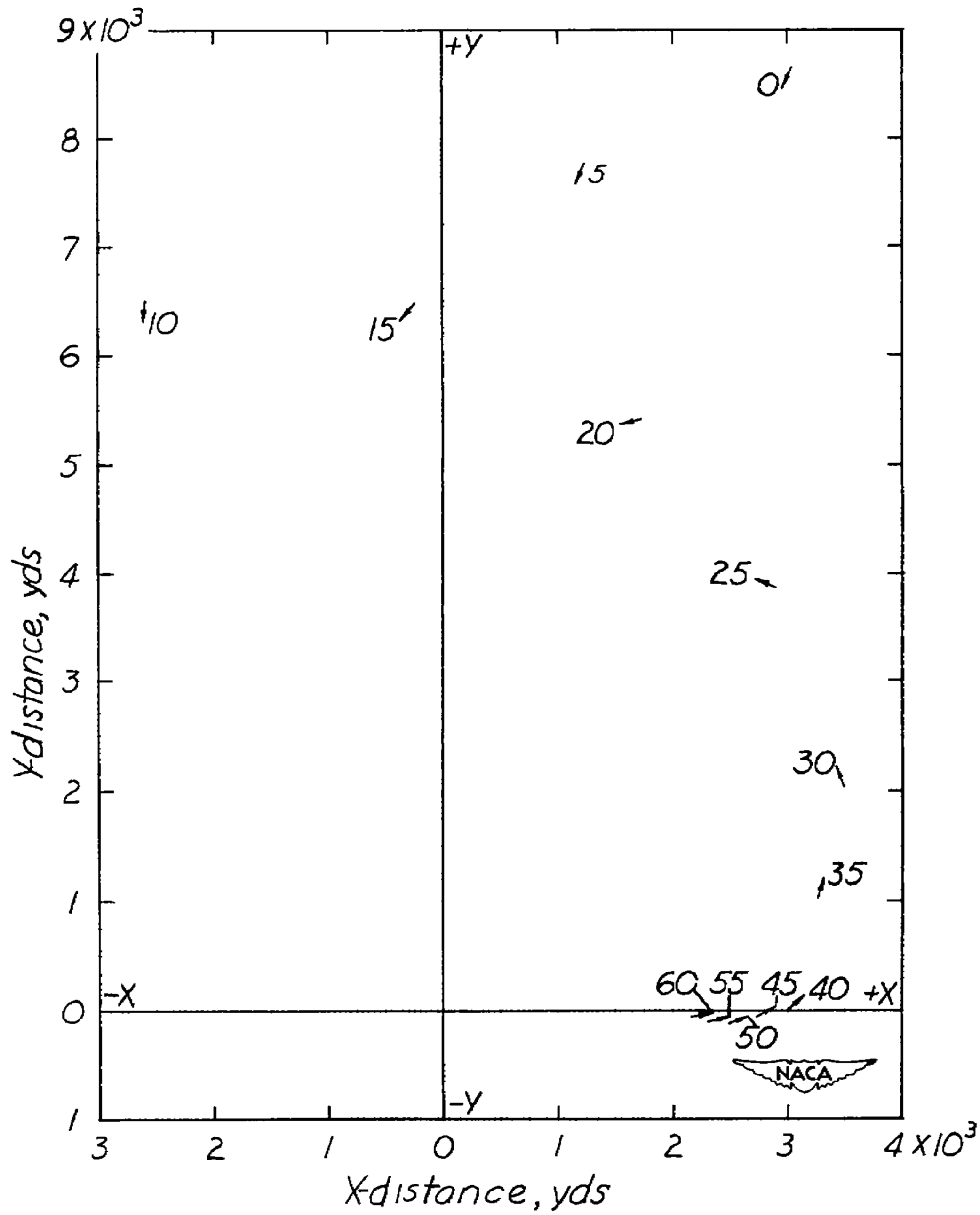
(a) Time history of various quantities pertaining to the interceptor airplane. Also the ground plot of the two airplanes recorded by radar tracking.

Figure 28.- Interceptor airplane attacking target airplane from a perpendicular encounter.



(b) Position of interceptor relative to target airplane. Target airplane is located at origin and is heading in +X-direction. Interceptor position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 28.- Continued.



(c) Position of target relative to interceptor airplane. Interceptor airplane is located at origin and is heading in +X-direction. Target position corresponds to tip of arrows and elapsed time in seconds from start of run is indicated beside each arrow.

Figure 28.- Concluded.

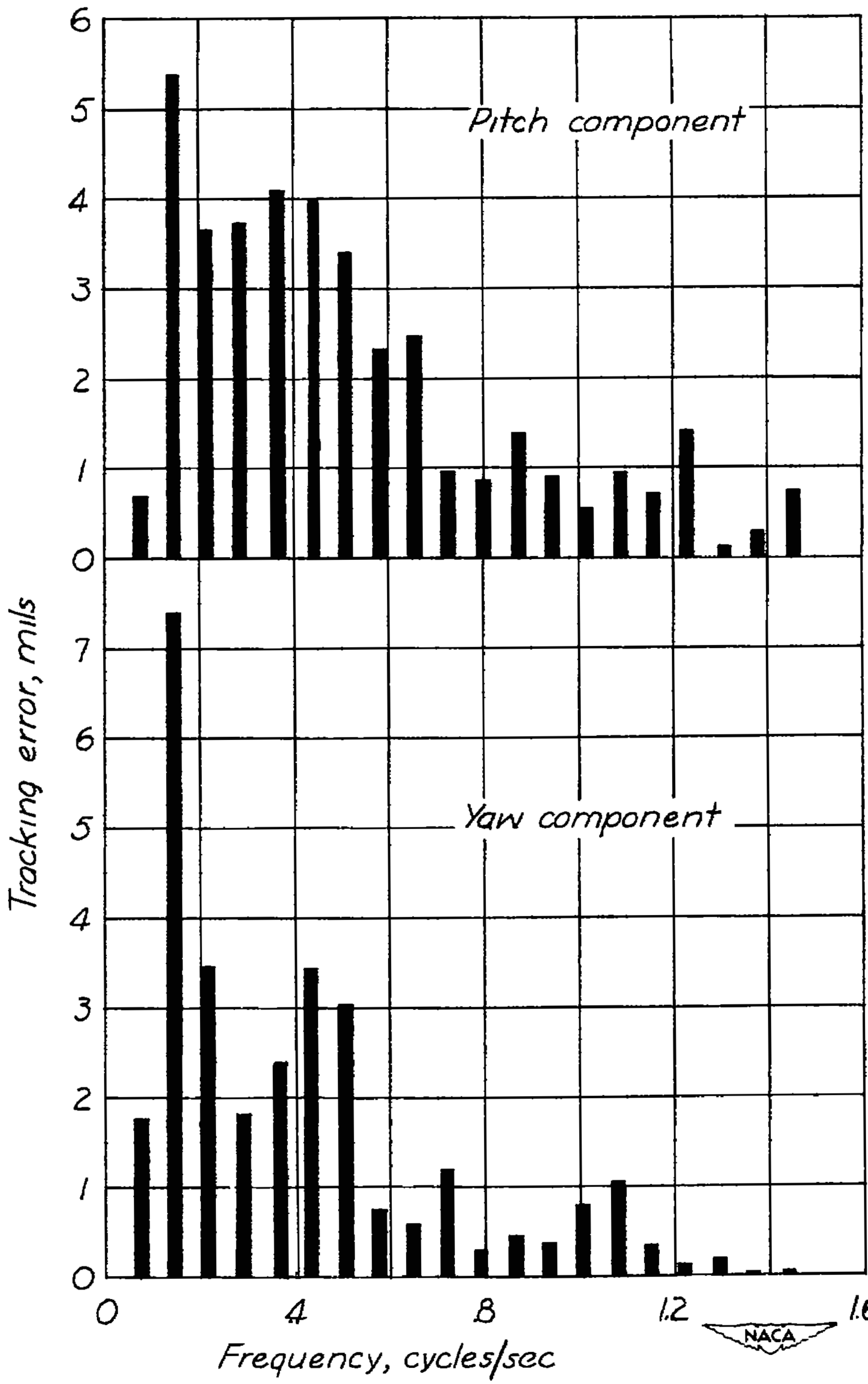


Figure 29.- Frequency content of the yaw and pitch components of the tracking error shown in the interception run presented in figure 22. Between 17.5 and 31.5 seconds.

~~SECURITY INFORMATION~~

[redacted]